

REPORT DOCUMENTATION PAGE

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14. ABSTRACT Modern rockets operate at supercritical pressures with respect to the propellants. Researchers need to understand mixing and combustion beyond liquid, gas states. Shear coaxial injectors are a common choice for cryogenic liquid rocket engines. Interactions of transverse acoustics with injector's own modes and mixing need to be understood for combustion instability. Need to understand differences in response to pressure and velocity nodes. Understand what non-dimensional numbers capture the mixing of typical injectors, characterize how geometry affects mixing.					
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Mixing in Shear Coaxial Jets with and without Acoustics

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Texas A&M University

29 March 2012



Statement of need

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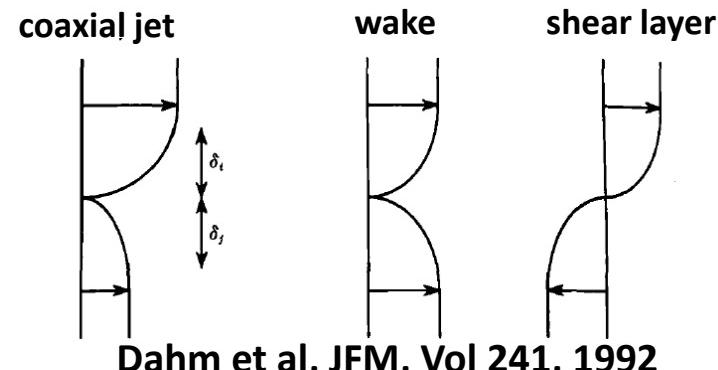
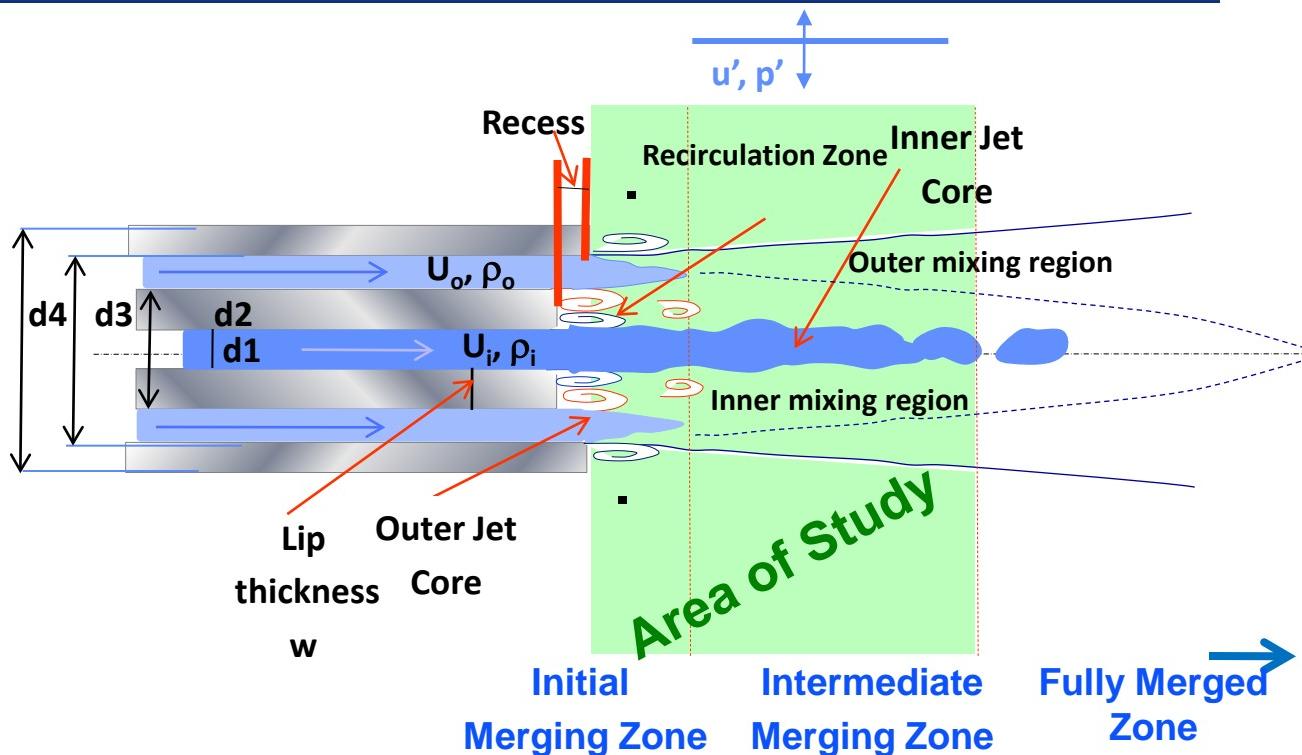
- Modern rockets operate at supercritical pressures with respect to the propellants
 - Need to understand mixing and combustion beyond liquid, gas states
 - Shear coaxial injectors are a common choice for cryogenic liquid rocket engines
 - Interactions of transverse acoustics with injector's own modes and mixing needs to be understood for combustion instability
 - Need to understand differences in response to pressure and velocity nodes
 - Understand what non-dimensional numbers capture the mixing of typical injectors
 - Characterize how geometry affects mixing



Relevant physics of shear coaxial jets

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1. Transverse Acoustic mode from chamber/siren
 - $f=f(c, \text{geometry})$
2. Acoustic modes for outer and inner jets
 - $f \sim c/2L - 2$ speeds of sound up and downstream
3. Wake resulting from inner post thickness
 - $St = fw/U_{ch}$
4. Shear layer instabilities
 - $St_\theta = f\theta/U_{ch}$
5. Jet preferred modes
 - $St = fD_{ij}/U_{ij}$

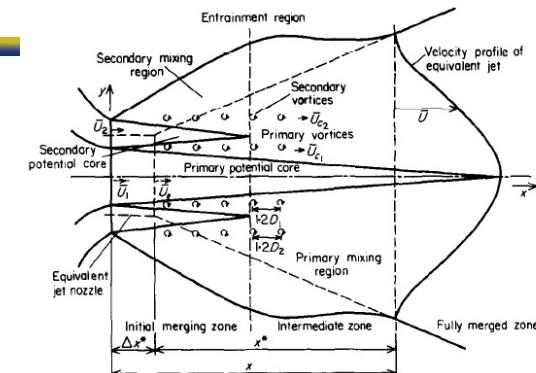




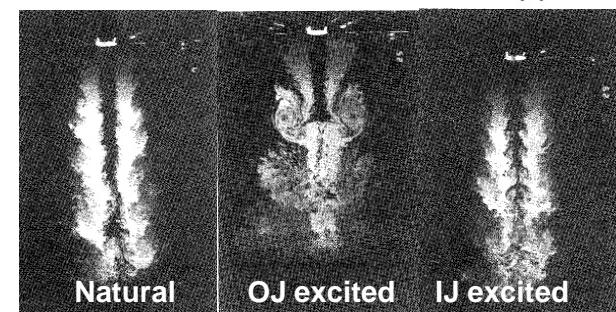
Highlights from previous work on jet instabilities 1/2

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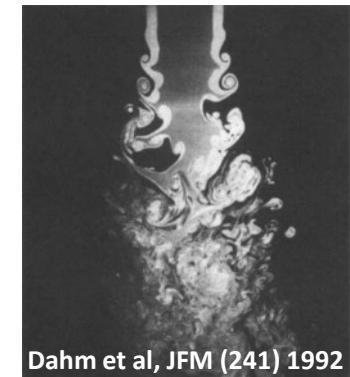
- Michalke, 1964
 - Linear stability theory for inviscid instability of a hyperbolic tangent velocity profile
- Crow and Champagne, 1971
 - Single jet preferred mode, $St_d = fd/U \sim 0.3$
- Ko et al, 1976-1989
 - Some of earliest detailed description of near field mixing for coaxial jets
- Boldman et al, 1975
 - Experimental and theoretical analysis for mixing of two air streams with different velocities – points out different vortex interactions, $St_i \sim 0.2$ (U_{ave})
- Gutmark and Ho, 1983
 - Collects previous results on jet preferred mode, St_d has a range from ~0.24-0.64
- Wicker and Eaton, 1994
 - Forces air inner and outer jets independently – observes vortex growth
- Dahm et al, 1992
 - Seminal pictures of different instabilities plus effect of absolute velocity and R



Kwan and Ko, J. Sound and Vibration, 48 (2), 1976



Wicker and Eaton, AIAA J, (32) No.3, 1994

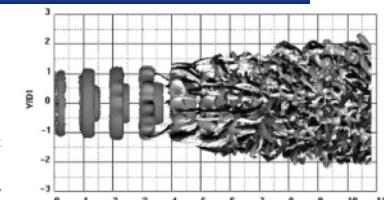
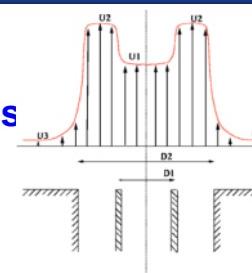


Dahm et al, JFM (241) 1992

Highlights from previous work 2/2

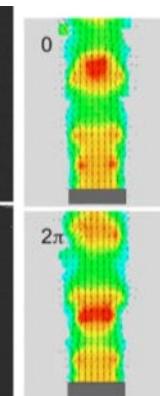
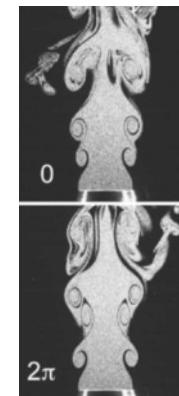
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- Balarac, da Silva, Metais et al (2003, 2007)
 - DNS analysis of coaxial jets - same density, top-hat profiles
 - Consider two shear layers, study effect of R
 - Consider axisymmetric and azimuthal excitation
- Buresti, Talamelli, Petagna (1994, 1998)
 - Air jets, same density, top-hat profile, $St_{do} = fd_o/U_{oj} \sim 0.3$ to 1, function of x/D_i
- Segalini, Talamelli, et al (2006, 2011)
 - Air jets, same density, top-hat profile, $St_{b(lip)} = fb(lip)/U_{average}$
- Birbaud, Ducruix, Durox, Candel (2006-2007)
 - Single air jets, low Re, laminar, top-hat profile, subjected to acoustic modulation
 - Systematic study of effect of modulation in terms of St_d , St_θ
- Tshohas, Canino, Heister (2004, 2009)
 - 2D unsteady CFD for LOX/H₂ elements but non-reacting
 - Unforced behavior, found $St_{lip} = fd_{lip}/U_{lox} \sim 0.10-0.25$
- Richecoeur, Scouflaire, Ducruix, Candel (2006)
 - Forced transverse acoustic excitation of flames

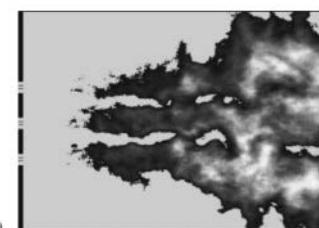
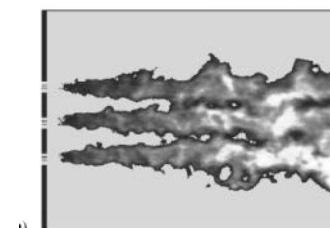


Balarac et al, Phys of Fluids (19), 2007

Segalini et al, Phys of Fluids (23), 2011



Birbaud et al, Phys of Fluids (19), 2007



Richecoeur et al, JPP (22) No 4, 2006

Relevant variables for cold-flow studies

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Geometry	Acoustics	Recess	Phase	VR	J	Coupling
Single Jet	On/Off	N/A	v' max	N/A		No
LAR_thickLip (injector 1)		1/2D1				No
SAR_thinLip (injector 2)	Off P' max U'max	1/2D1 D1 0	2-phase P<Pc		0.1-20	
SAR_thickLip (injector 3)		0	P>Pc T>Tc T<Tc		0.1-20	Yes& No
LAR_thinLip (injector 4)		0				



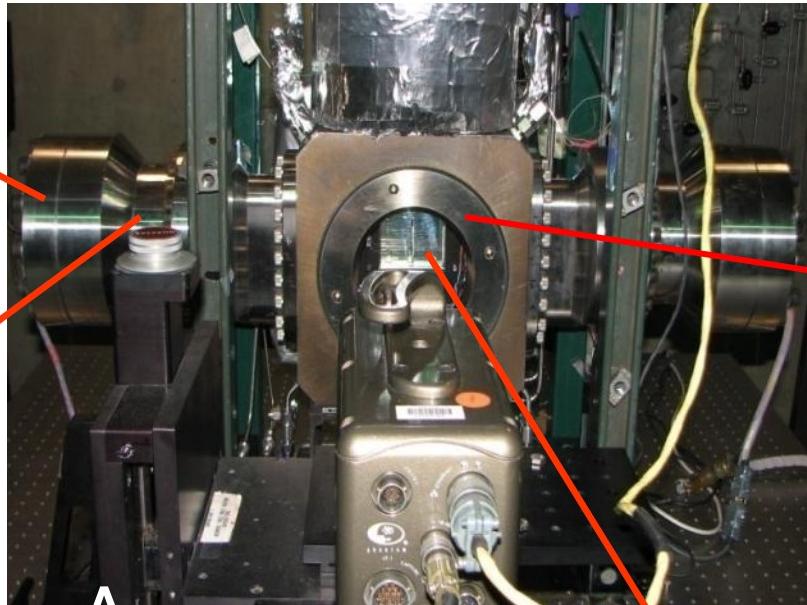
Experimental setup – EC-4

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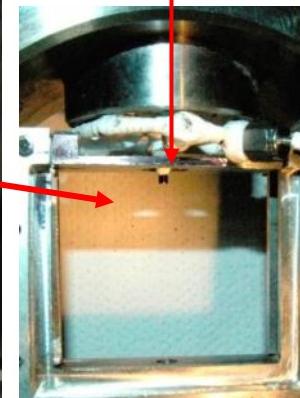
Piezo-Siren



Waveguide

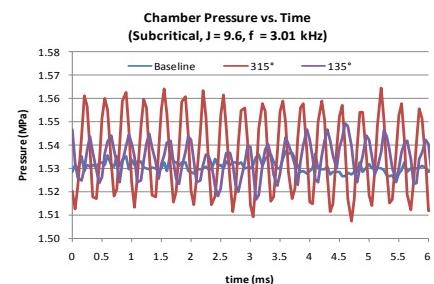
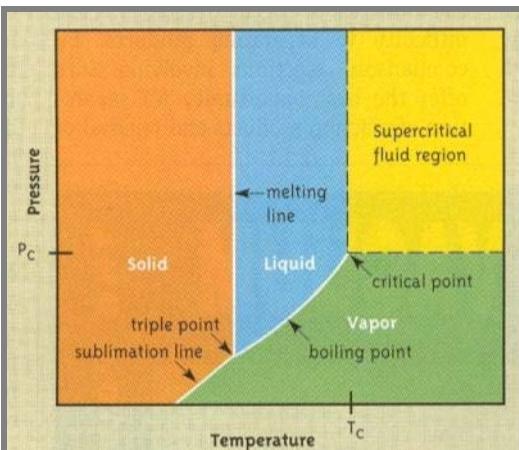


Coaxial Injector



Inner Chamber

$f \approx 3\text{kHz}$

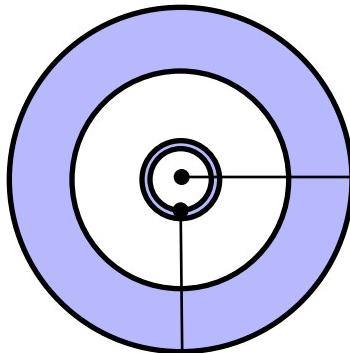


Thermocouple and P transducer

Geometric Rationale

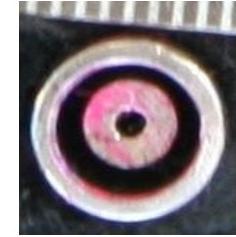
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LAR_ThinLip

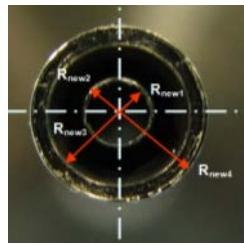


Similar I.D.

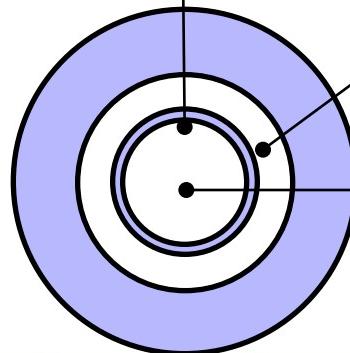
LAR_ThickLip



SAR_ThinLip



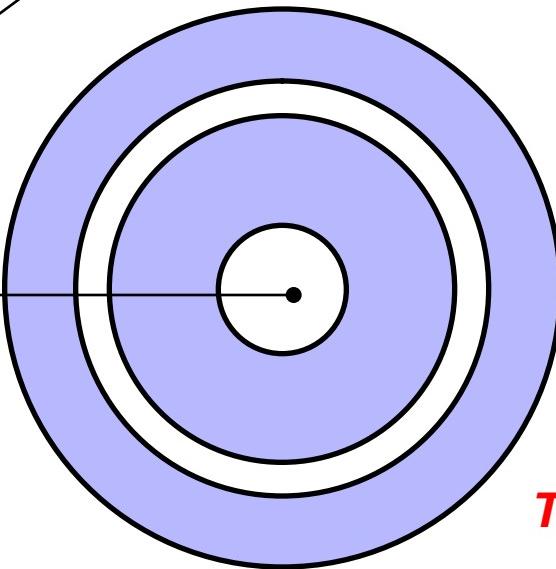
Similar lip thickness/I.D.



Similar Outer Area

similar I.D.

SAR_ThickLip



Two recesses

	D1 (mm)	D2 (mm)	D3 (mm)	D4 (mm)	t/D $t=(D_2-D_1)/2$	Ao/Ai
LAR_thickLip	0.51	1.59	2.42	3.18	1.05	12.9
SAR_thinLip	1.40	1.65	2.44	3.94	0.09	1.6
SAR_thickLip	1.47	3.96	4.70	6.35	0.84	2.9
LAR_thinLip	0.70	0.89	2.44	3.94	0.13	10.6

SAR, LAR -> Small, Large Area Ratio
ThickLip, ThinLip -> Post lip thickness

Chronological progression (only coaxial results are summarized in what follows)

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- Single jets, no coaxial flow
 - Davis et. al. (Ph.D. thesis) – single jets, no coaxial flow
- Coaxial jets
 - Davis et al. (Ph.D. thesis) – LAR thick
 - Leyva et.al. – LAR_thick
 - Rodriguez et. al. (Ph.D. thesis) – LAR_thick, SAR_thin
 - Graham et. al. – SAR_thin, two recesses
 - Teshome et. al. (Ph.D. thesis, expected April 2012) – complete all four geometries
 - Also complete modal analysis of earlier geometries
- Future: Combusting coaxial jets
 - Wegener et. al. (Ph.D. thesis) (in process)
 - Article 219 facility funds

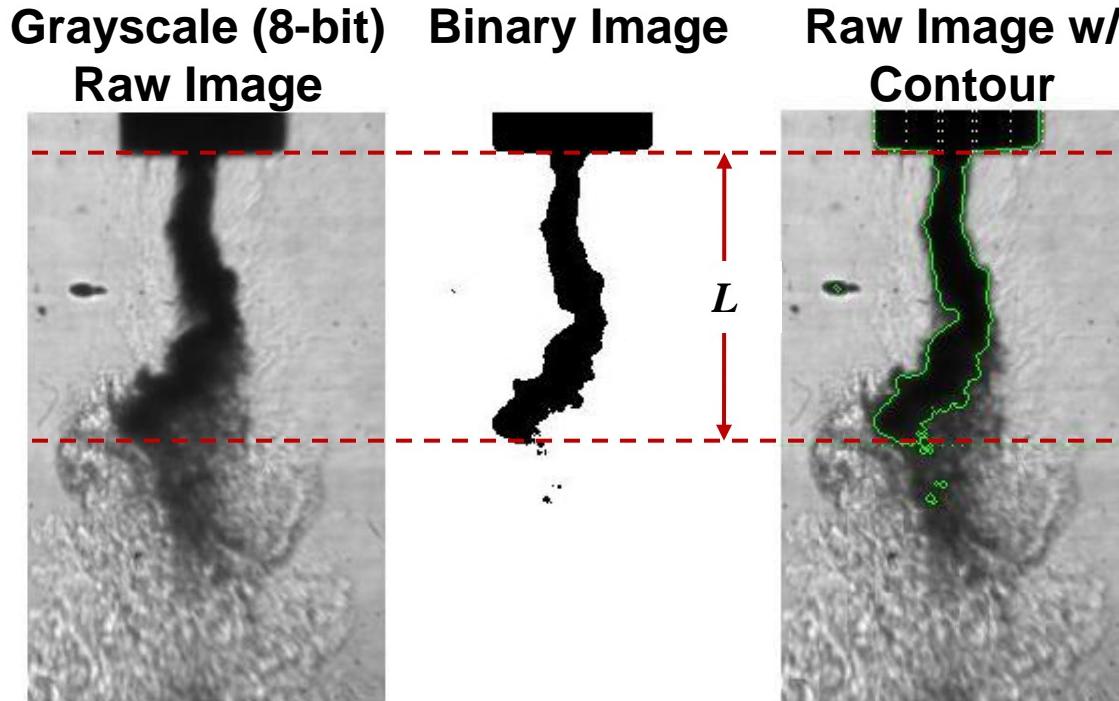




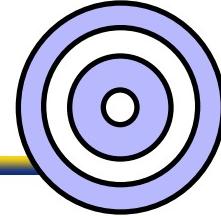
Dark-Core Length Measurement

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- First raw grayscale images were converted to binary images
- A contour was drawn around the “dark-column” in the binary image
- Axial length of the dark-column measured and defined as the Dark-Core Length, L

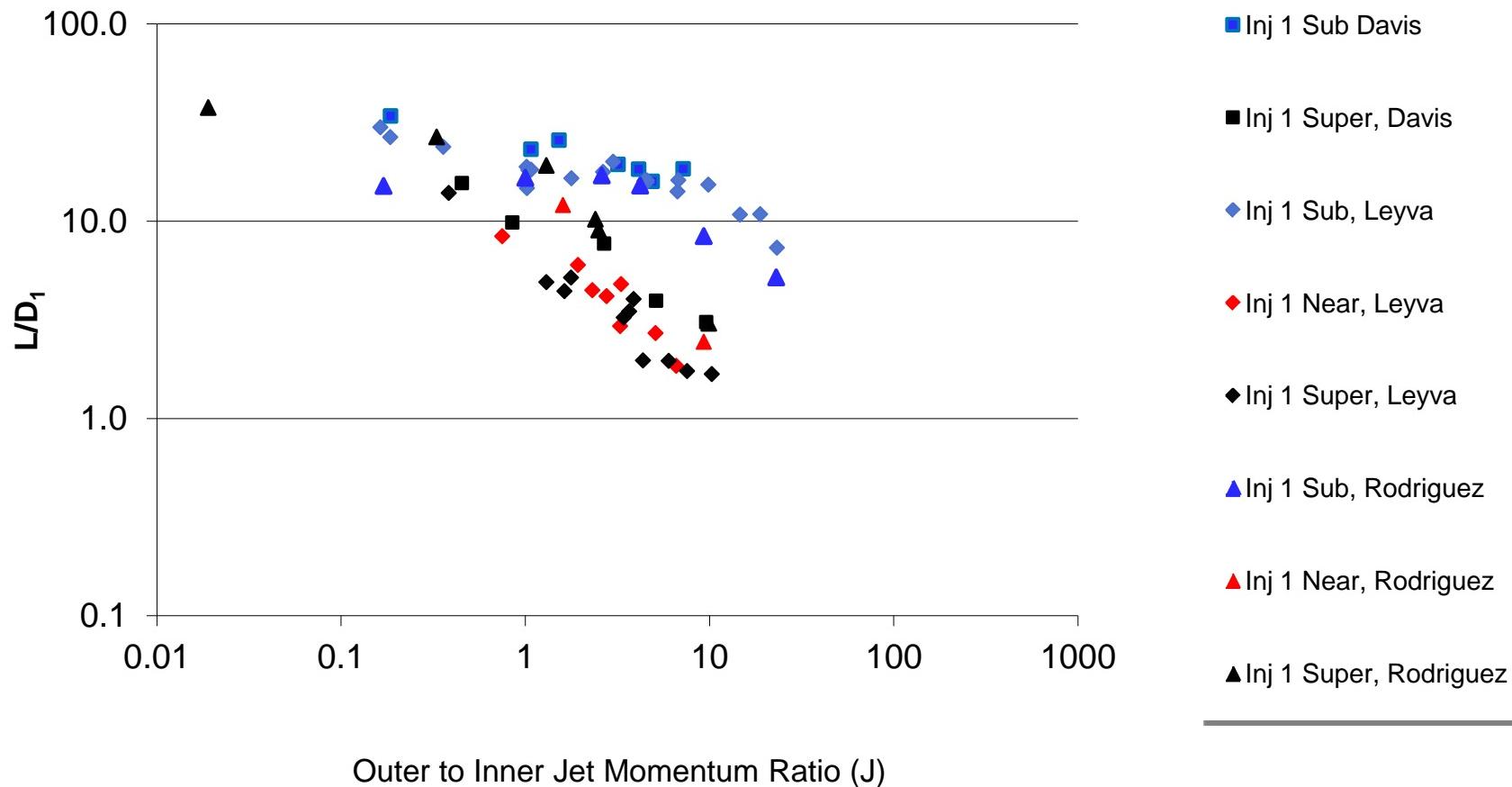


Dark Core Length – SAR-thick – All data

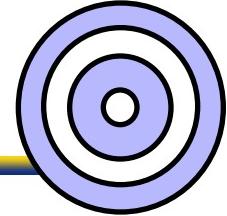


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Dark Core Length without Acoustics

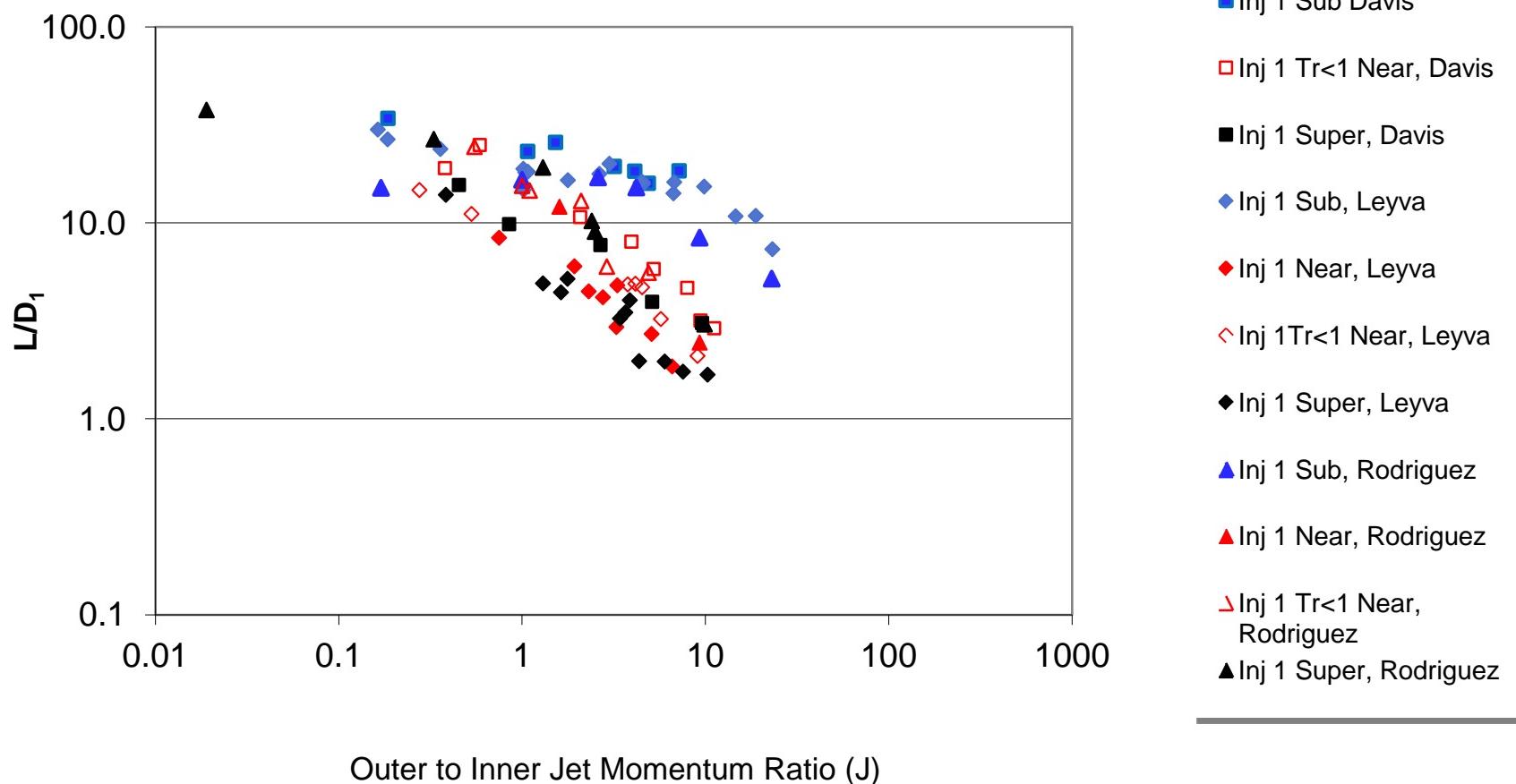


Dark Core Length – SAR-thick – All data



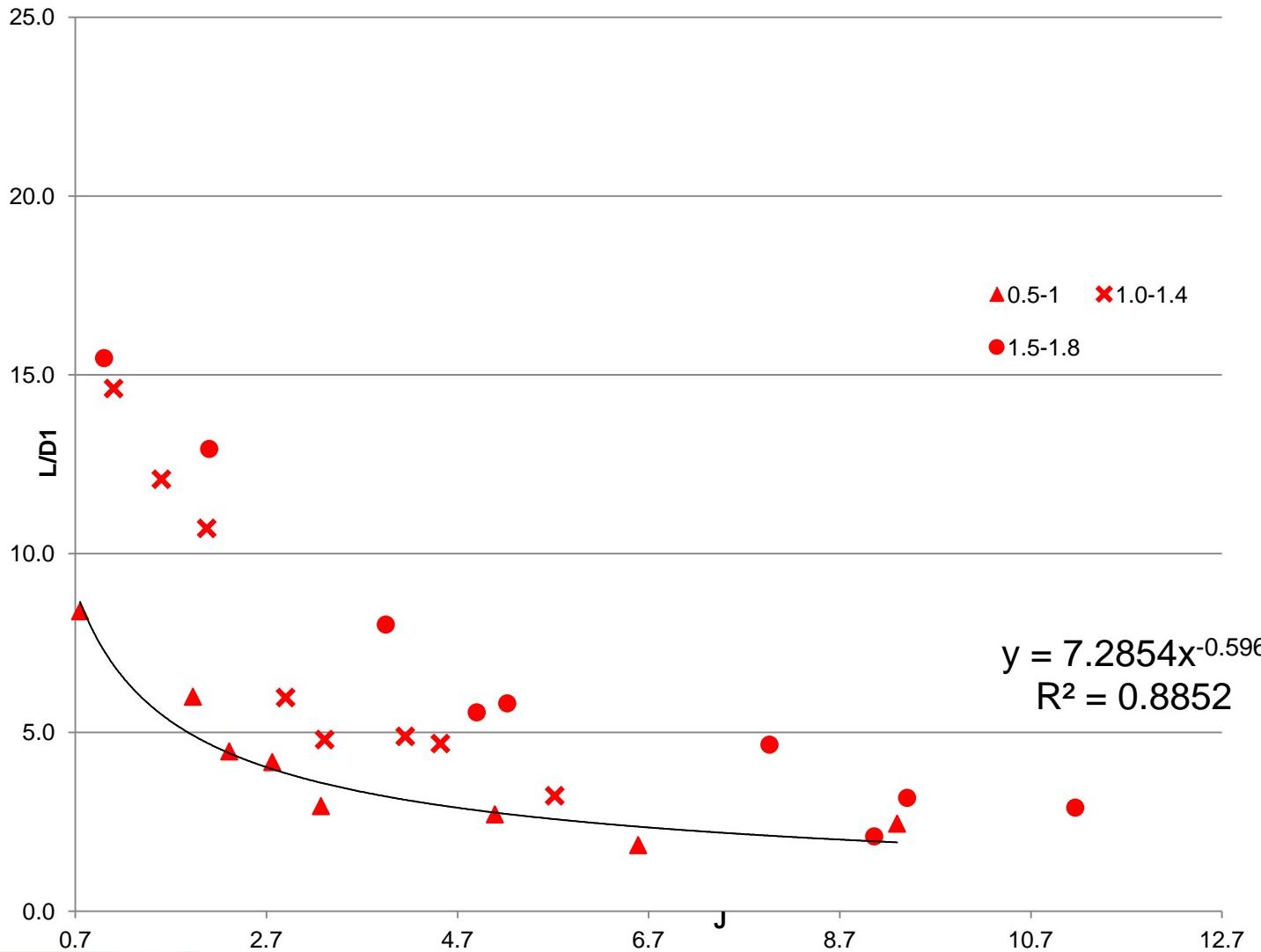
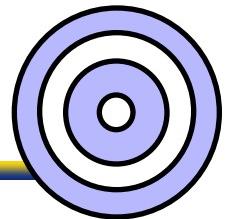
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Dark Core Length without Acoustics

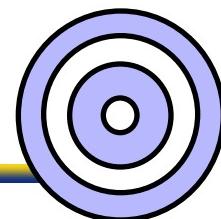


Dark Core Length – SAR thick – supercritical pressure

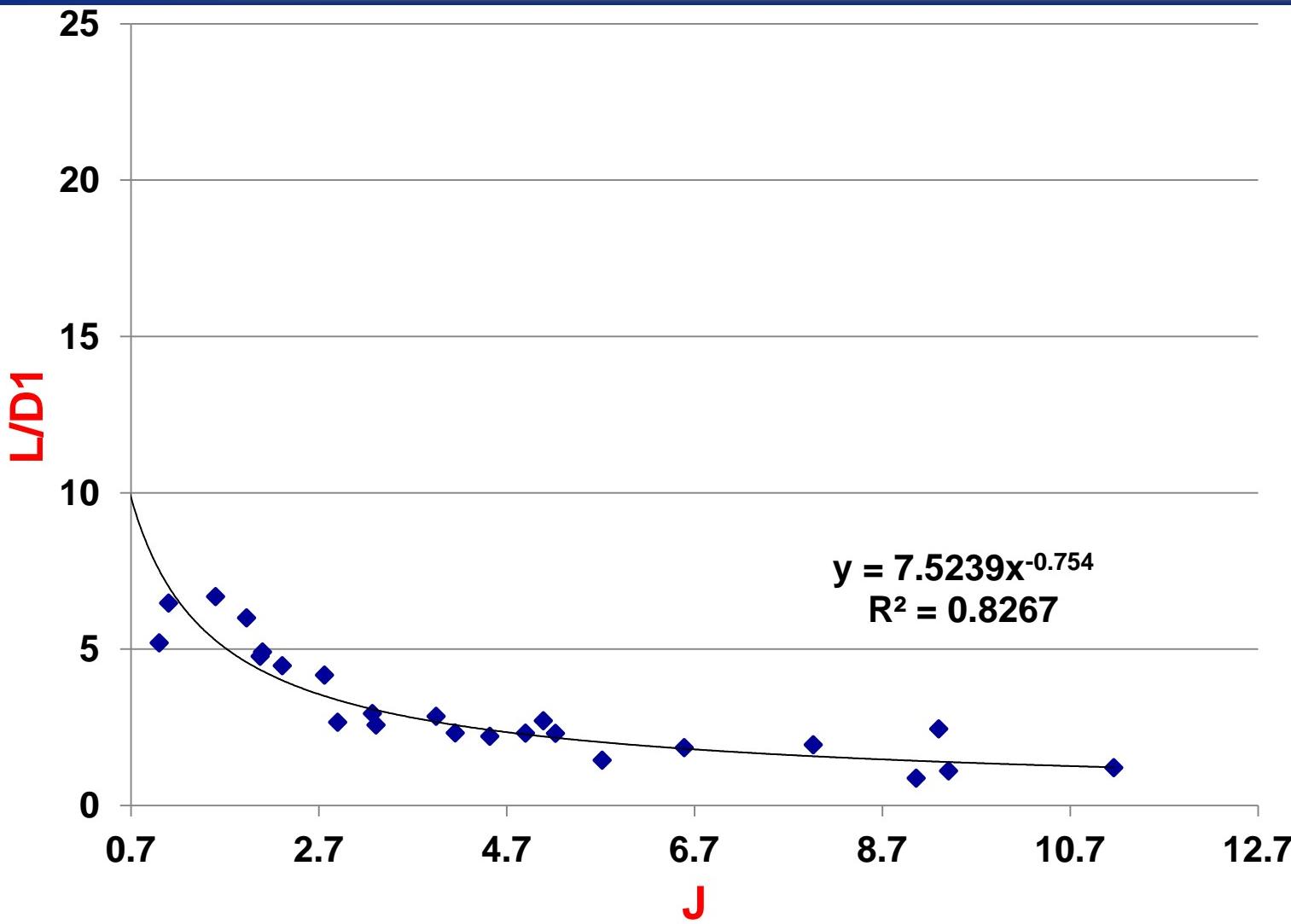
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Dark Core Length – SAR thick – supercritical pressure



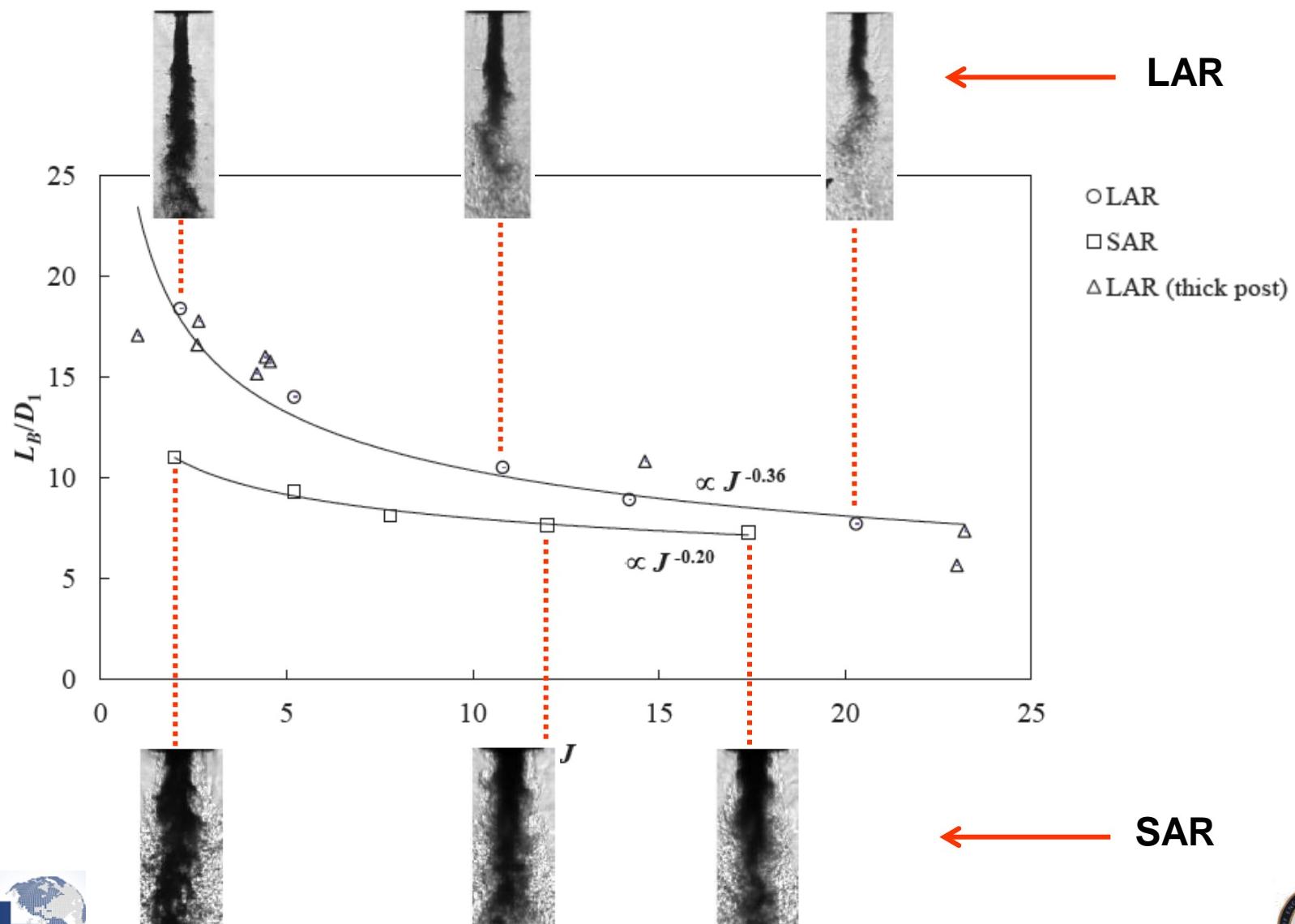
14





Baseline Dark-Core Lengths

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Acoustic Field Set-Up: Pressure Antinode

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- Pressure antinode (PAN) – condition of maximum pressure perturbation in the acoustic field
- Piezo-sirens forced in-phase
- Superposition of quasi-1D acoustic waves traveling in opposite directions \Rightarrow PAN at the jet location (geometric center of test section)

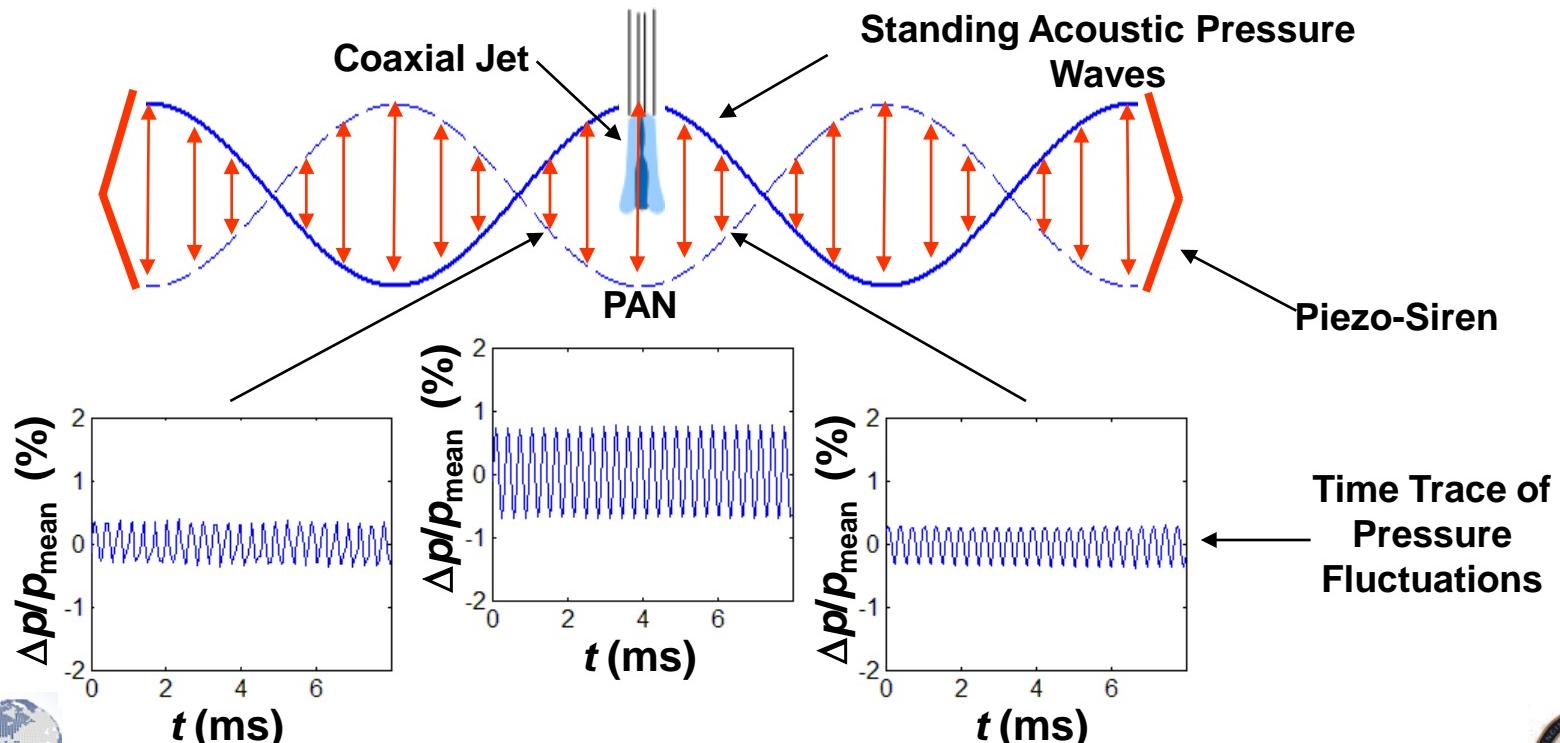
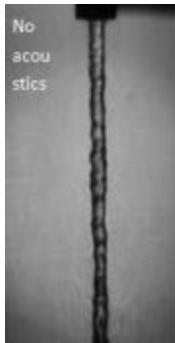


Image interpretation key

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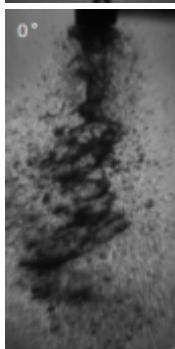
Baseline:
Acoustics
off



pressure = fixed

$$J (\rho_o u_o^2 / \rho_i u_i^2) = \text{fixed}$$

0°
Acoustics on
PAN, VN



PN – pressure node - Min
PAN – pressure antinode - Max
VN – velocity node
VAN – velocity antinode

"Pressure coupled"

180°
PN, VAN



Largest difference
expected from 0°
"Velocity coupled"



Image interpretation key

18

pressure = fixed

$J (\rho_o u_o^2 / \rho_i u_i^2) = \text{fixed}$

Acoustics on
 0°

PAN, VN

"Pressure coupled"

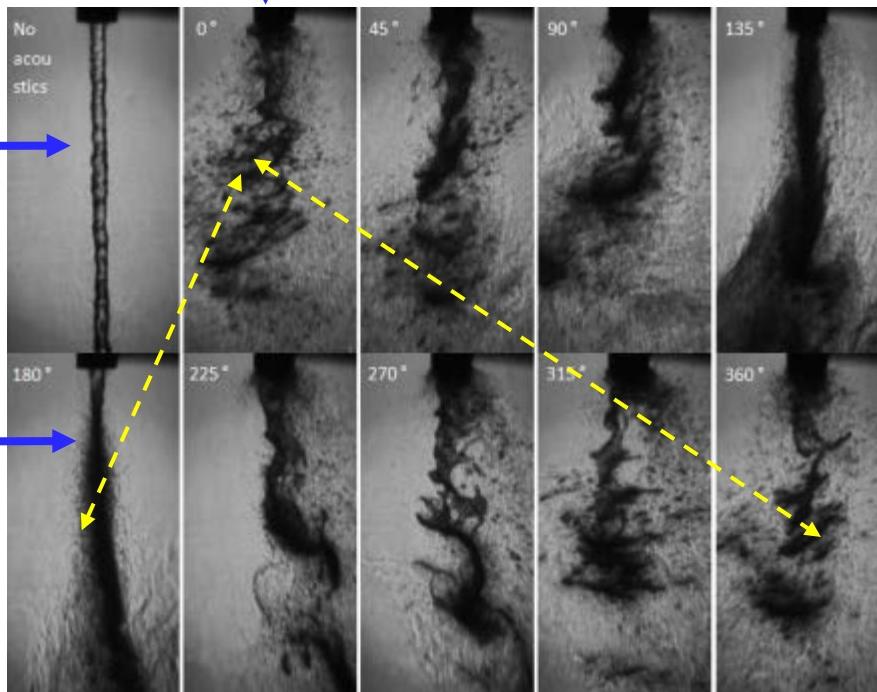
Subsequent images:
acoustics on;
Phase increases by 45°

Baseline:
Acoustics
off

180°

PN, VAN

Largest difference
expected from 0°
"Velocity coupled"



PN – pressure node - Min
PAN – pressure antinode - Max
VN – velocity node
VAN – velocity antinode

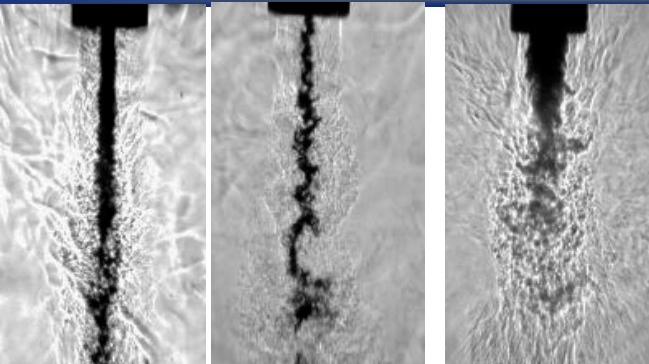
360°
should look
similar to 0°



Sub-Critical Pressure: Two Geometries

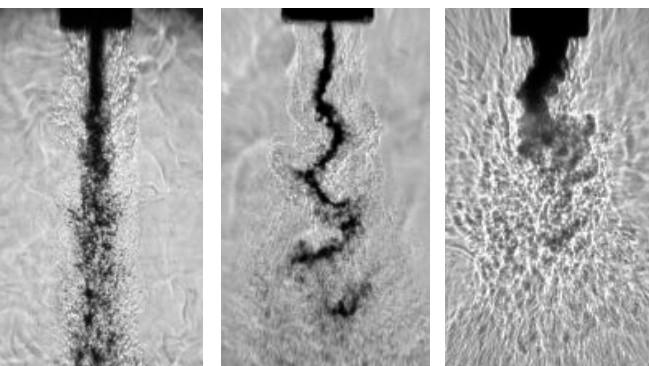
LAR_thickLip

Baseline



PAN

P
antinode



PN

P node

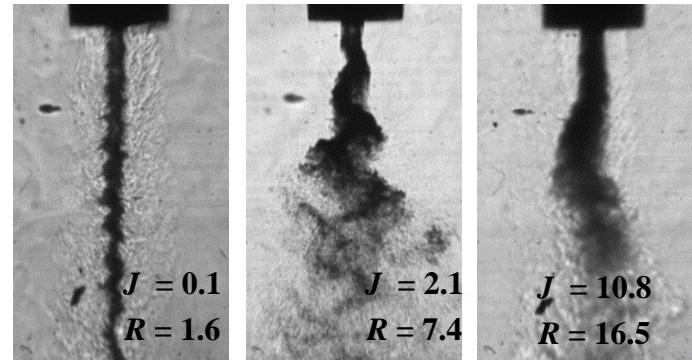
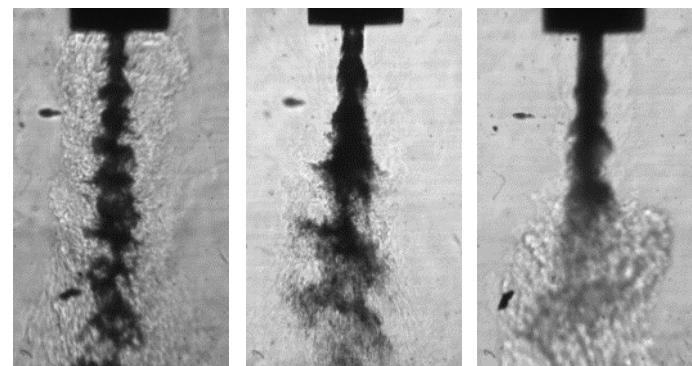
$$J = \rho_o u_o^2 / \rho_i u_i^2$$
$$R = u_o / u_i$$

$$J = 0.2$$
$$R = 2.0$$

$$J = 2.6$$
$$R = 7.6$$

$$J = 9.6$$
$$R = 14$$

LAR_thinLip



$$J = 0.1$$
$$R = 1.6$$

$$J = 2.1$$
$$R = 7.4$$

$$J = 10.8$$
$$R = 16.5$$

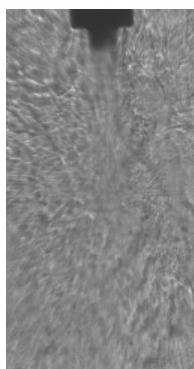
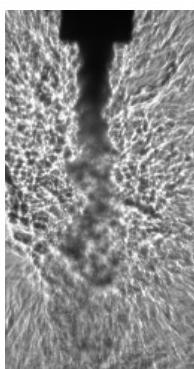
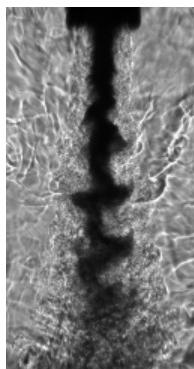


Near-Critical Pressure: Two geometries

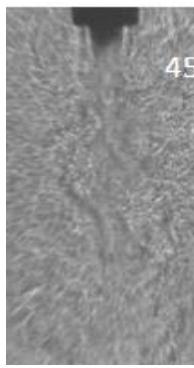
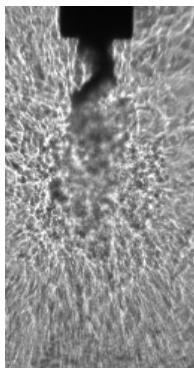
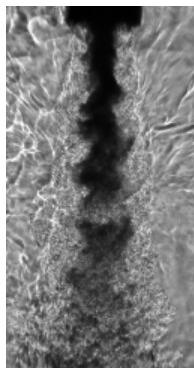
20

LAR_thickLip

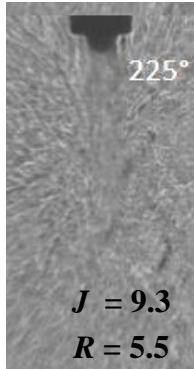
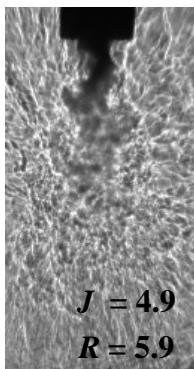
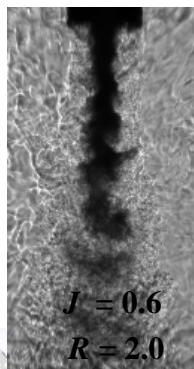
Baseline



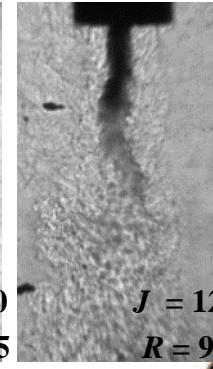
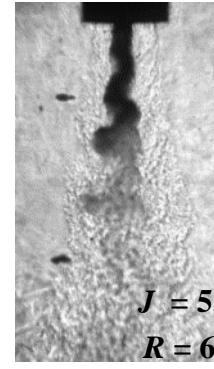
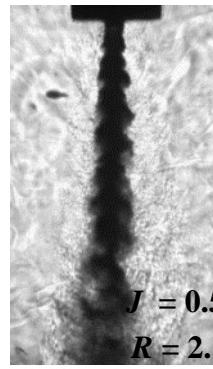
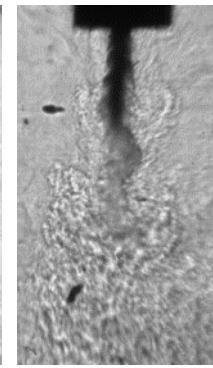
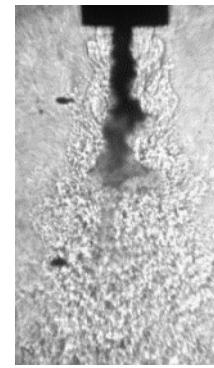
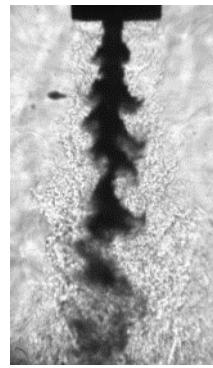
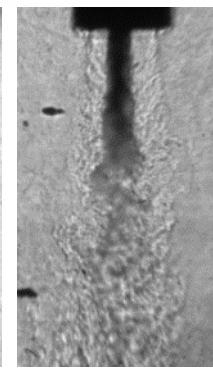
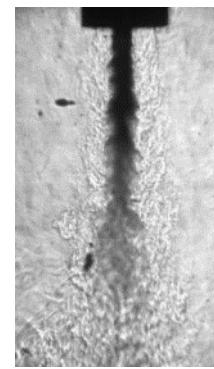
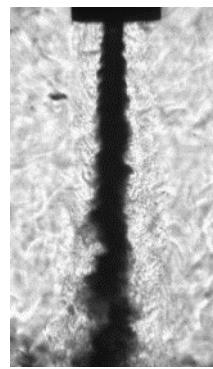
PAN



PN



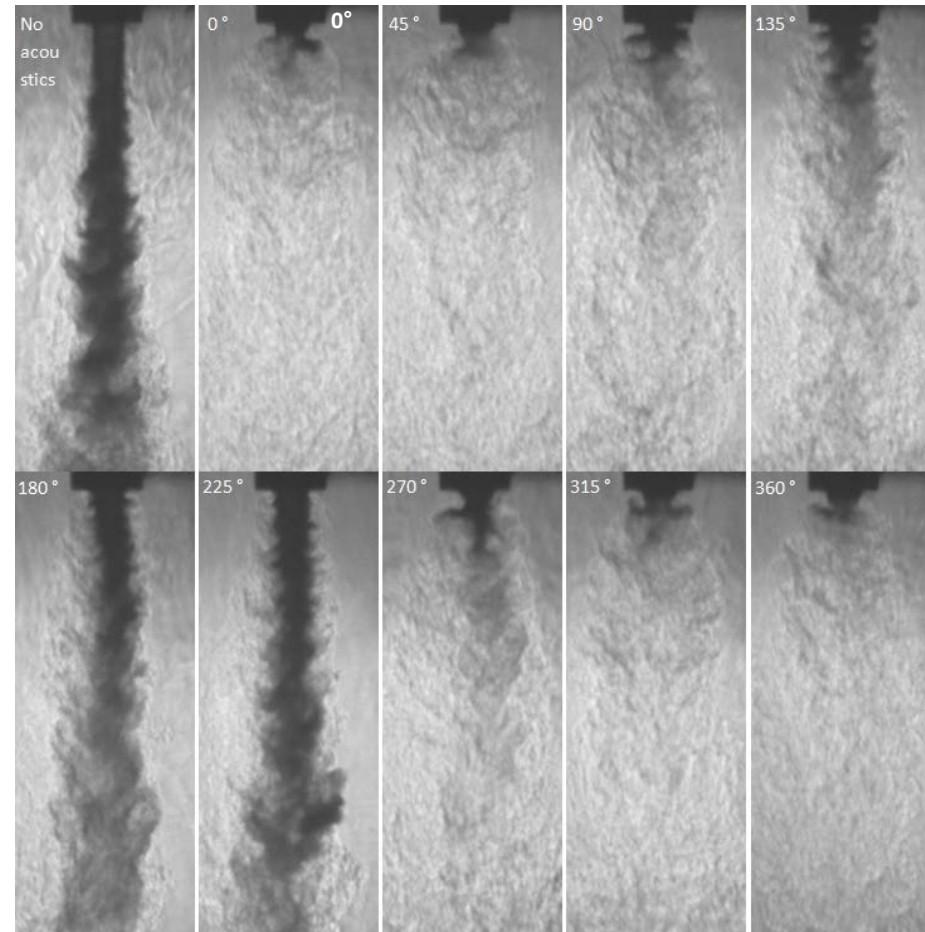
LAR_thinLip





SAR_thinLip

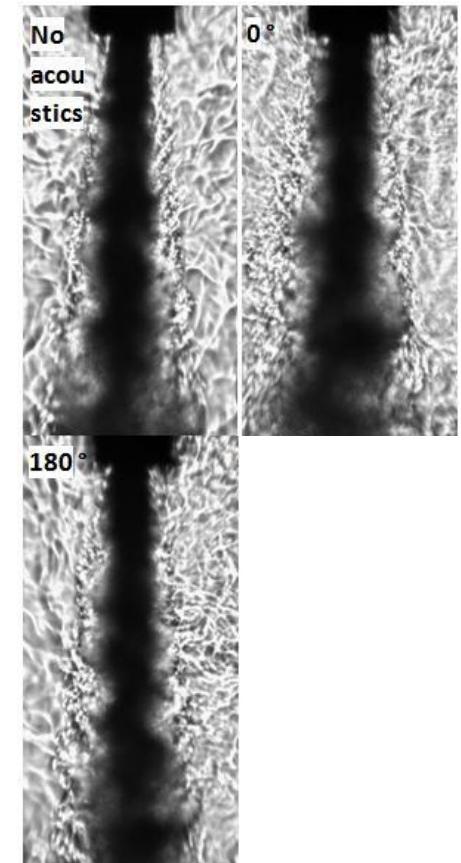
21



$Pr=1.05, J=1.7, p'/p=0.32\%$

Coupled to Outer Jet Acoustic Mode

- Nearcritical conditions
 - No jet bending observed
 - large vortical structures generated when coupled to injector mode
 - Reduction of dark core can be as large as 90%
 - More clear response of jet to pressure antinode
- Subcritical conditions
 - Same mode – vortical structures
 - Not as dramatic reduction as with nearcritical cases



$Pr=1.05, J=2.2,$
 $p'/p=0.25\%$

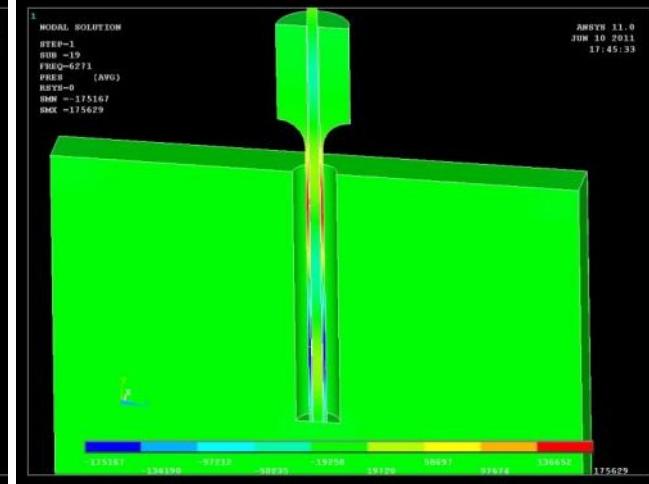
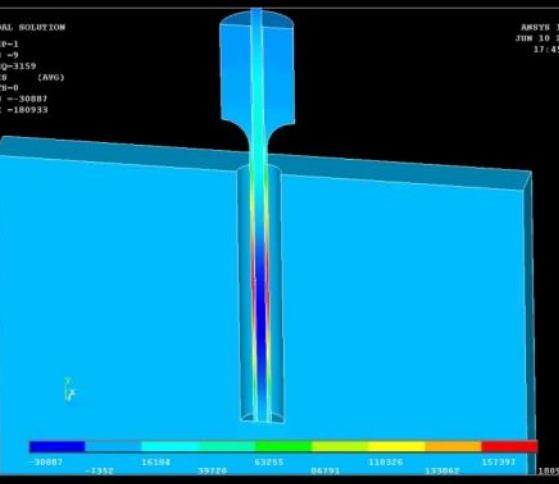
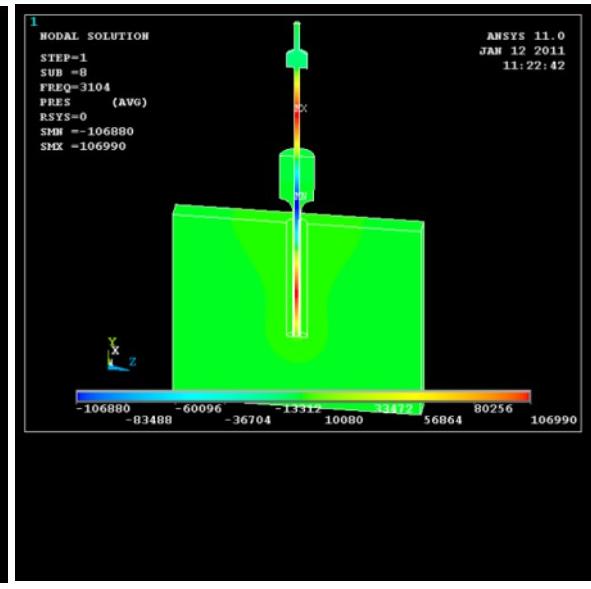
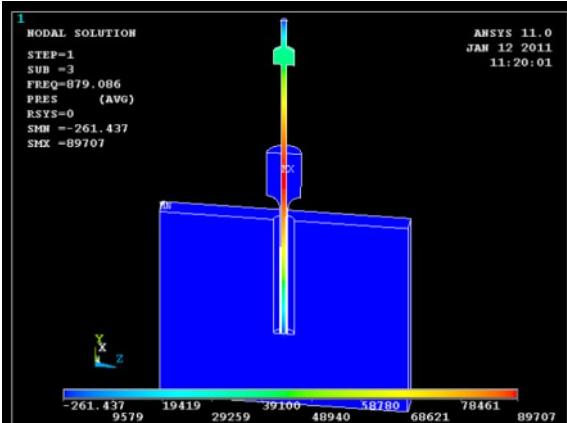
Non Coupled

$Pr=1.05, J=0.5, R=2$

$Pr=1.05, J=0.5, R=1.3$

Acoustic Analysis for Injectors

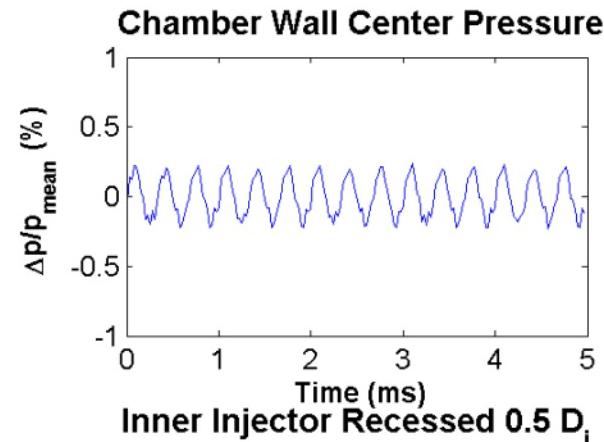
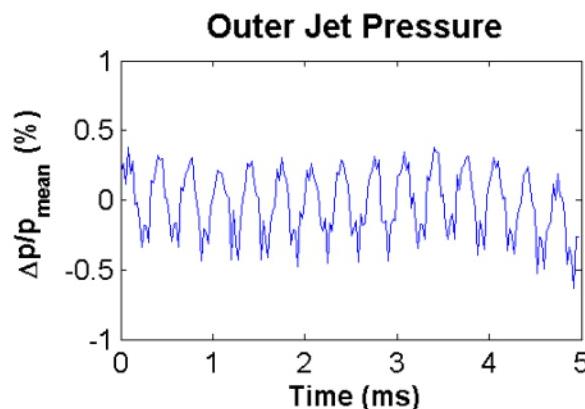
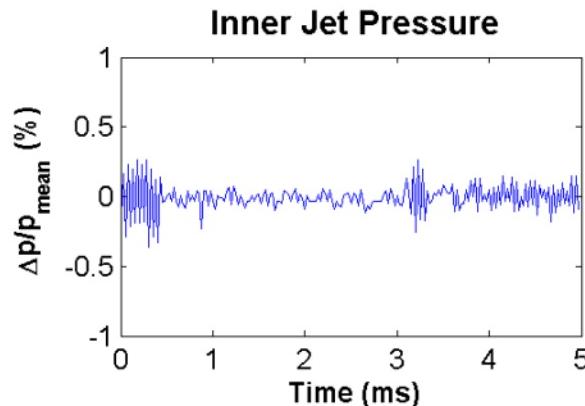
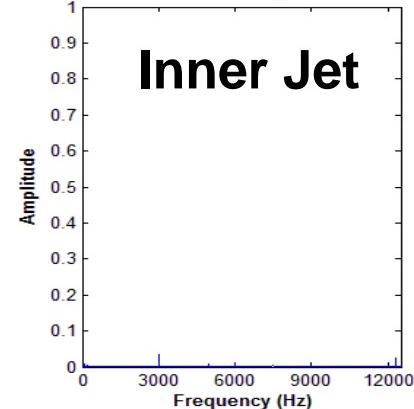
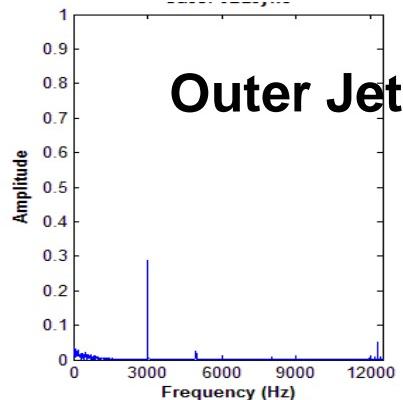
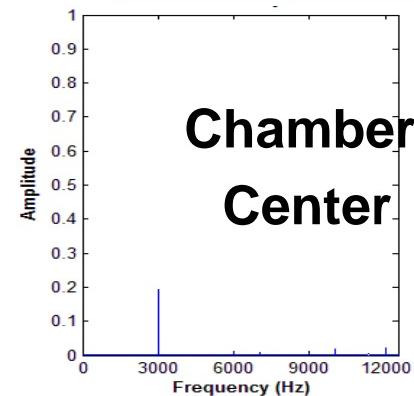
In collaboration
with Jeff Muss and
Rory Davis, Sierra
Engineering



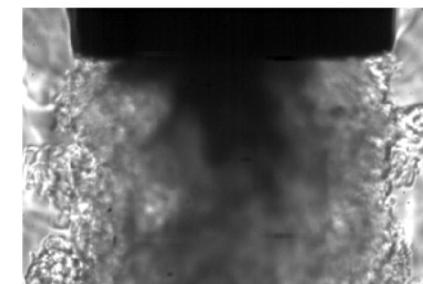
Have more accurately
computed the acoustic
modes for the inner and
outer jets for constant and
linearly varying
temperatures for
subcritical and
supercritical pressures

New analysis: synchronized p' and images taken with microscopic lens

23



$Pr = 1.03, J = 5.1, VR = 5.9$
Forcing Condition: 3000 Hz, Maximum Δp

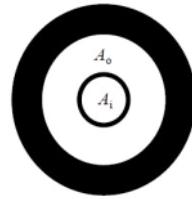


$U_o = 6.25 \text{ m/s}, U_i = 1.06 \text{ m/s}, T_o = 165 \text{ K}, T_i = 118 \text{ K}$

Distribution A: Approved for Public Release; Distribution Unlimited

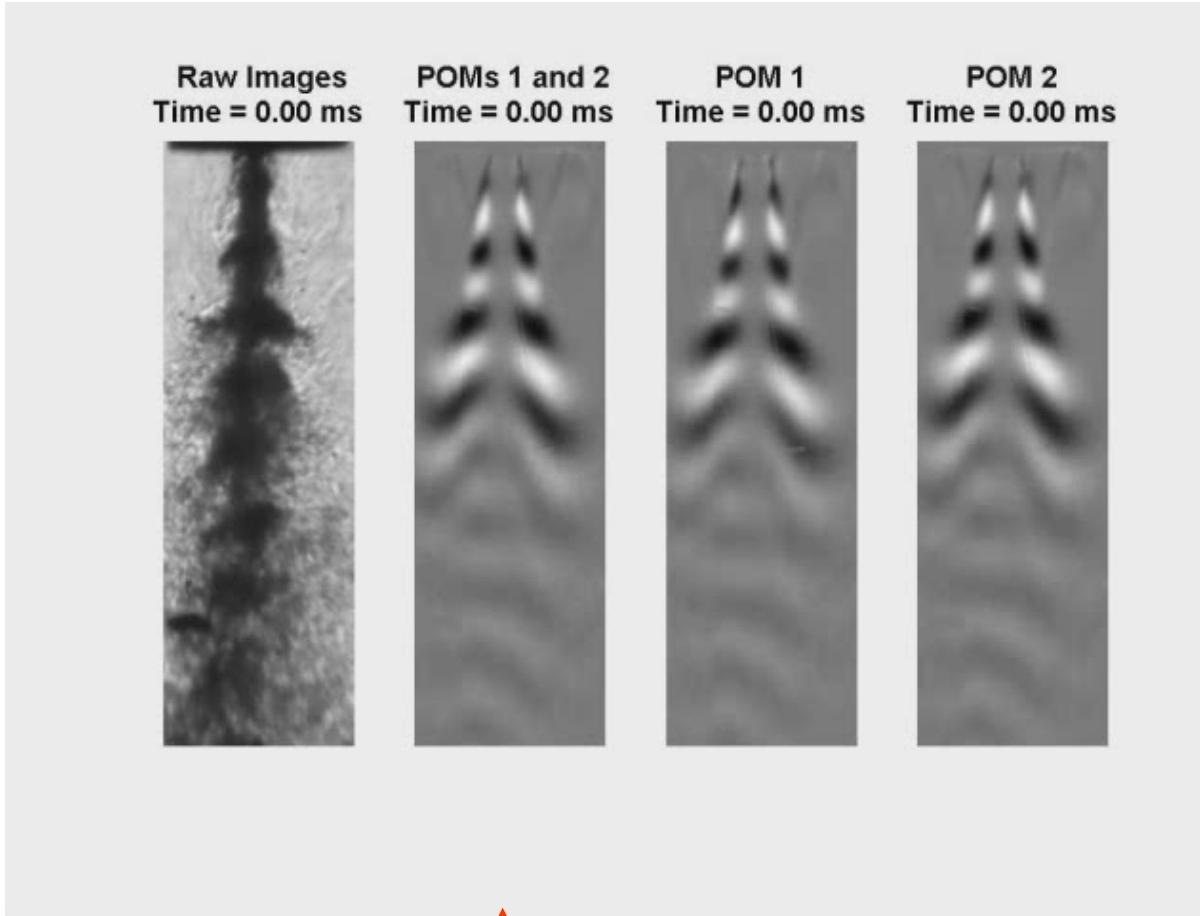


Sample Animation – PAN ($f_F = 3.14$ kHz)



24

- LAR thin $Pr = 0.44$,
 $J = 0.5$

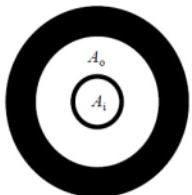


Superposition of POMs 1 and 2 Resulted in Downstream Propagating Structures

Distribution A: Approved for Public Release; Distribution Unlimited

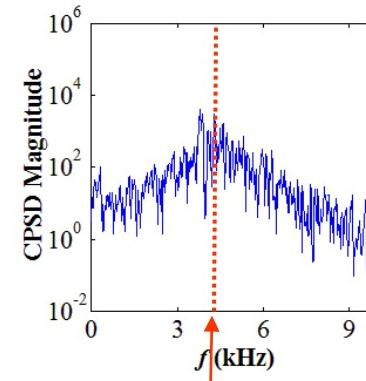
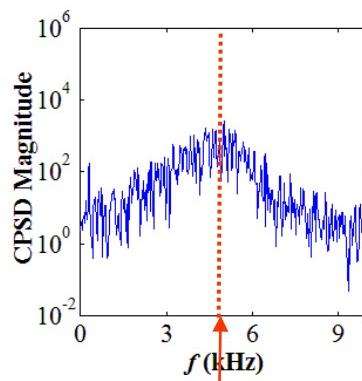
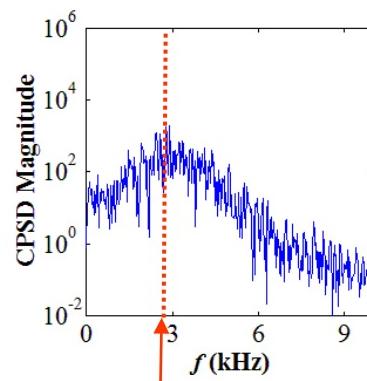
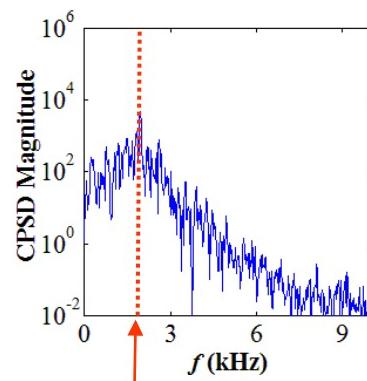
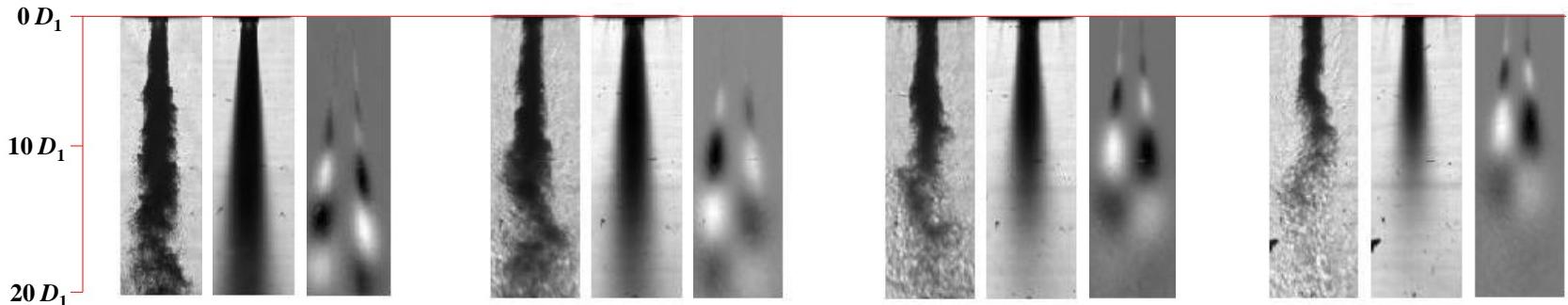


Results – LAR-thin, $Pr = 0.44$, Baseline



25

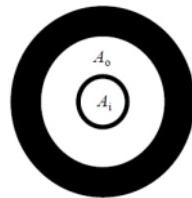
- Antisymmetric flow structures indicated helical type flow instabilities for all J

 $J = 2.1$ $J = 5.2$ $J = 11$ $J = 20$ 

Characteristic peaks broadened and shifted to higher frequencies with increasing outer jet velocity

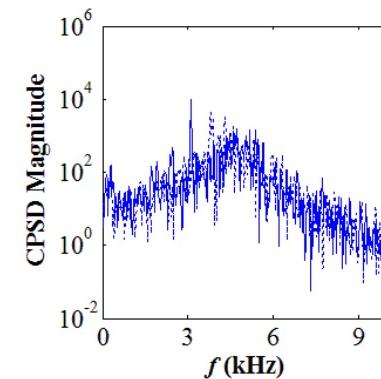
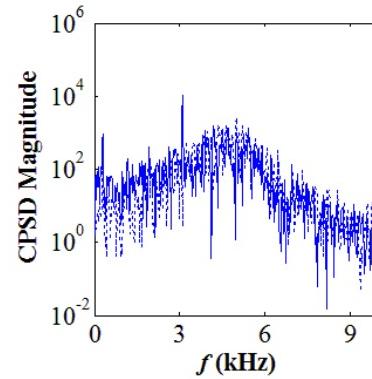
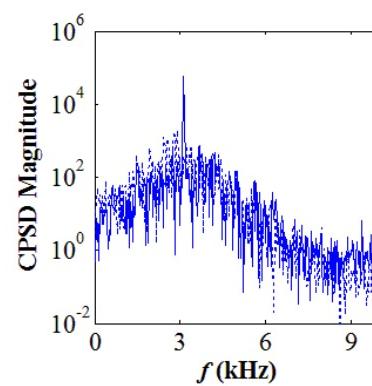
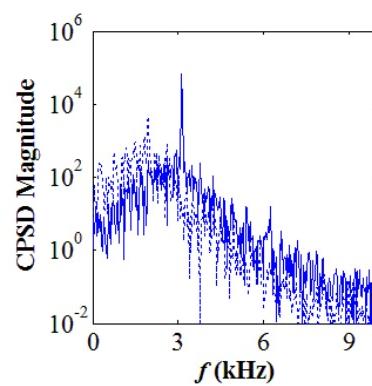
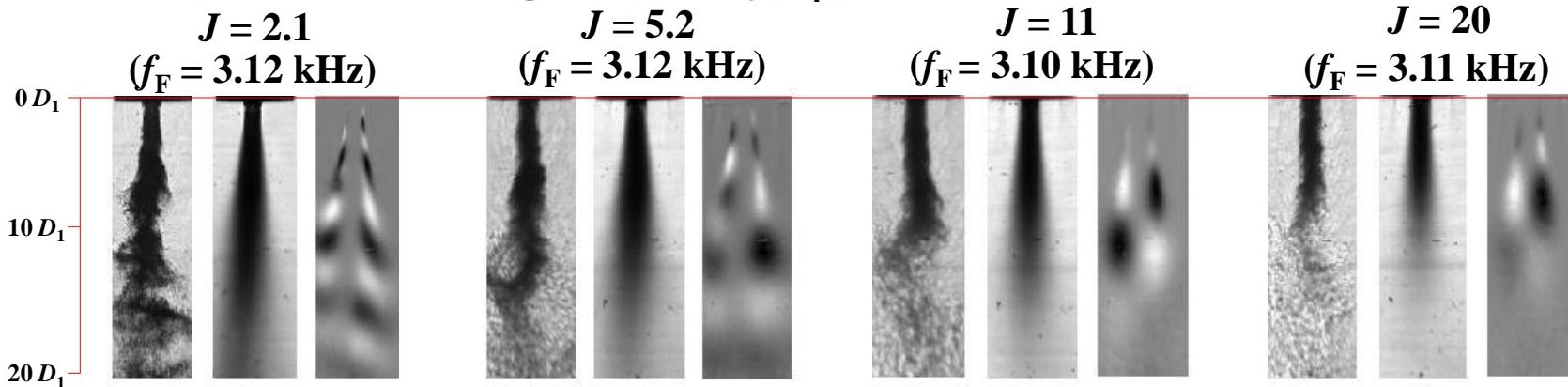


Results – LAR-thin, $Pr = 0.44$, PAN



26

- Gradual shift from symmetric to antisymmetric flow structures with increasing J
- Response at forcing frequency, f_F , dominant at lower J

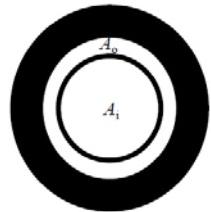


Baseline

PAN

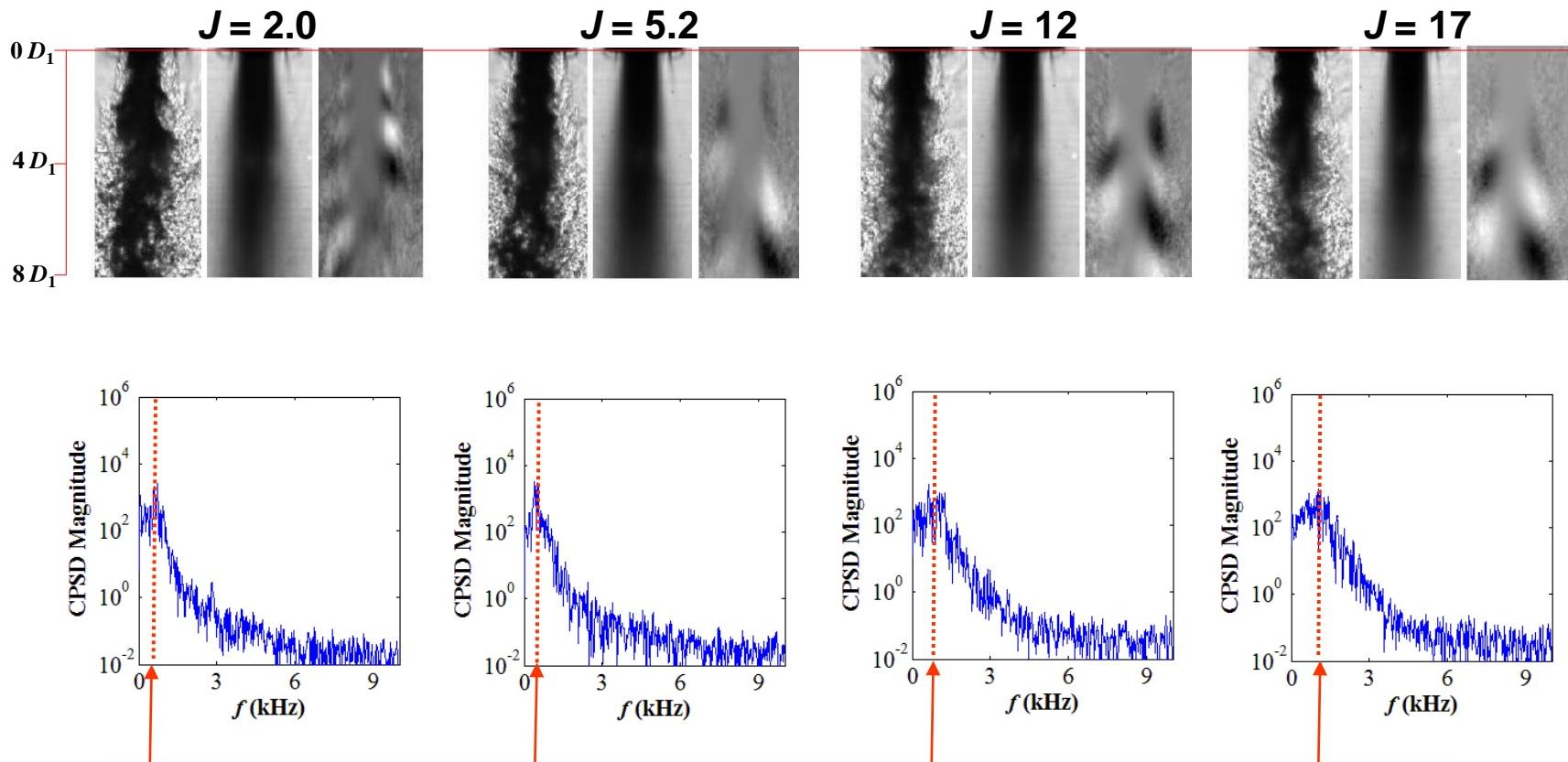


Results – SAR, $Pr = 0.44$, Baseline



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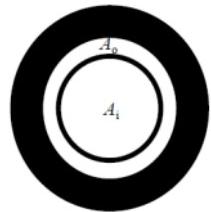
- Helical type flow instabilities became more well-defined with increasing J



Unlike LAR flows, characteristic peaks showed minimal variation in frequency with outer jet velocity

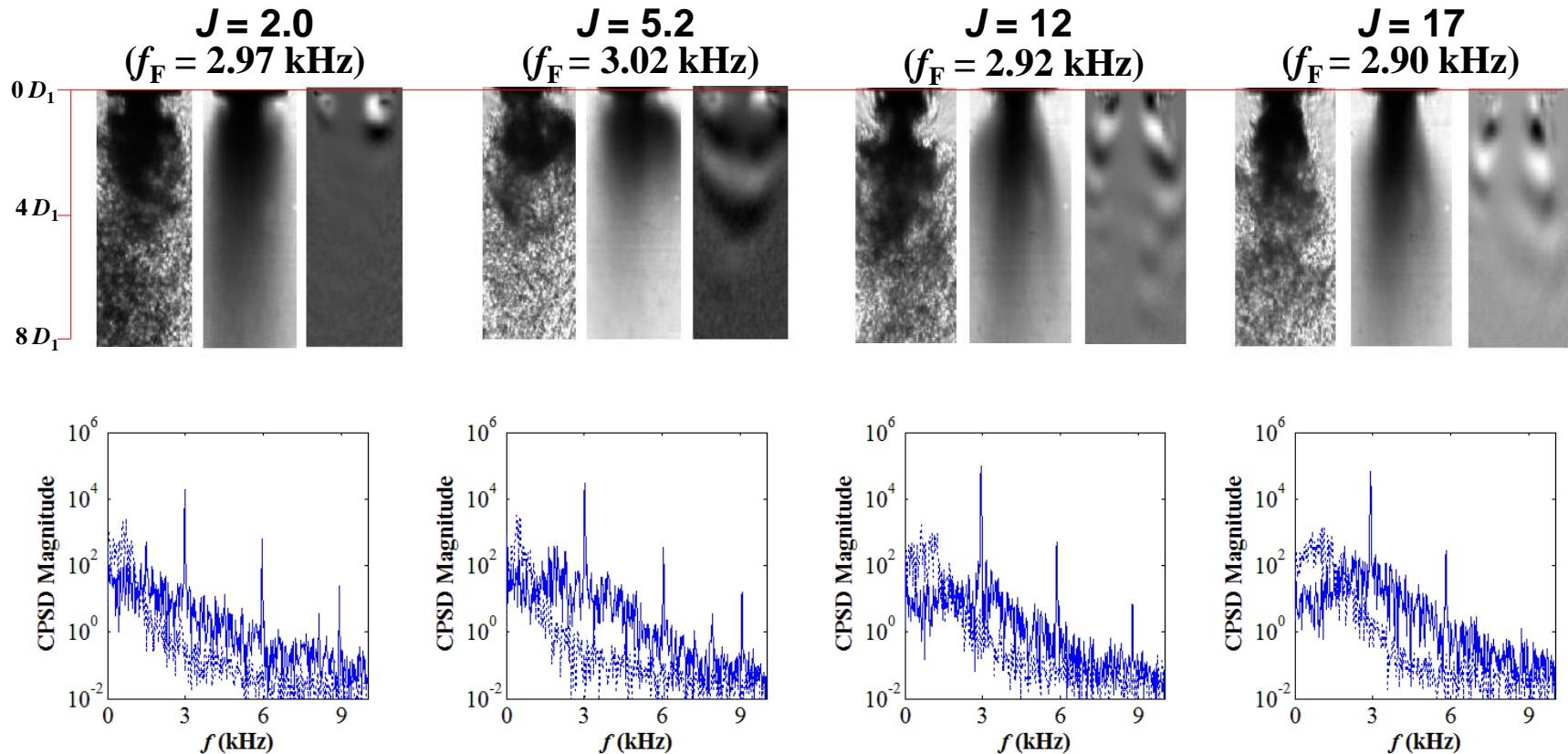


Results – SAR, $Pr = 0.44$, PAN



28

- Symmetric structures persist despite increasing J
- Response at f_F strong at highest J

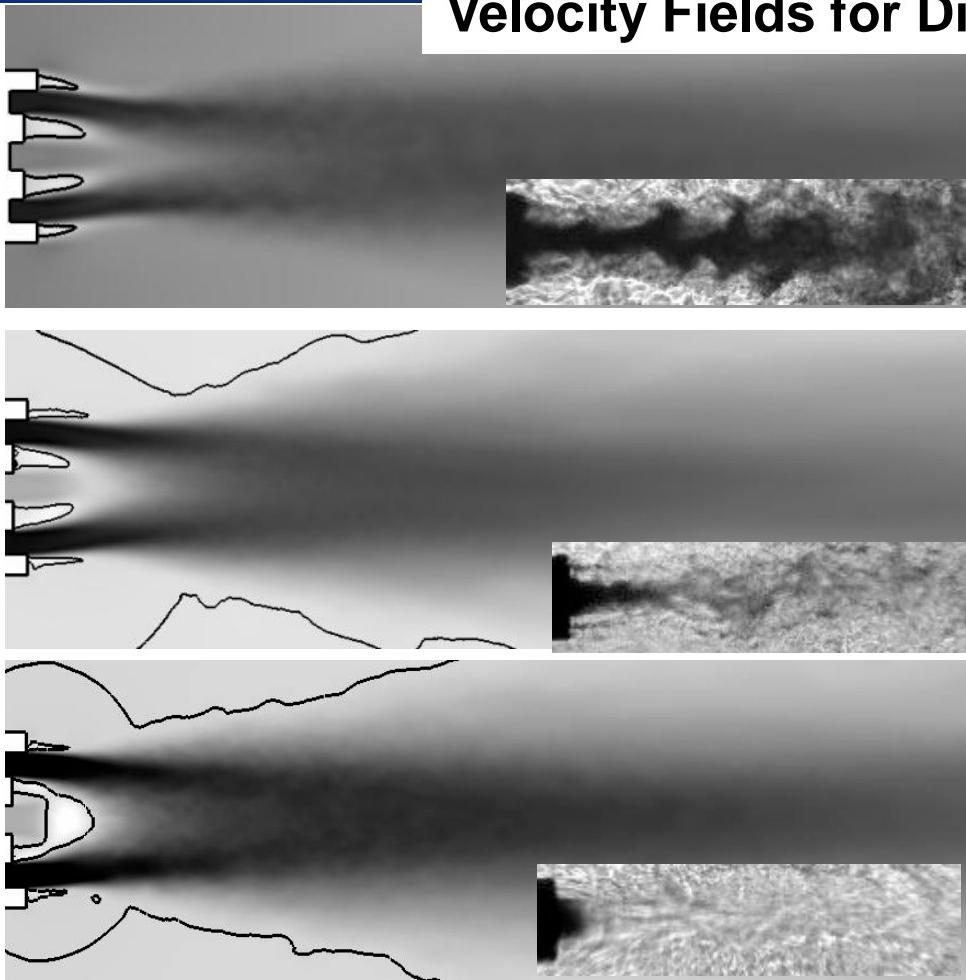


Baseline

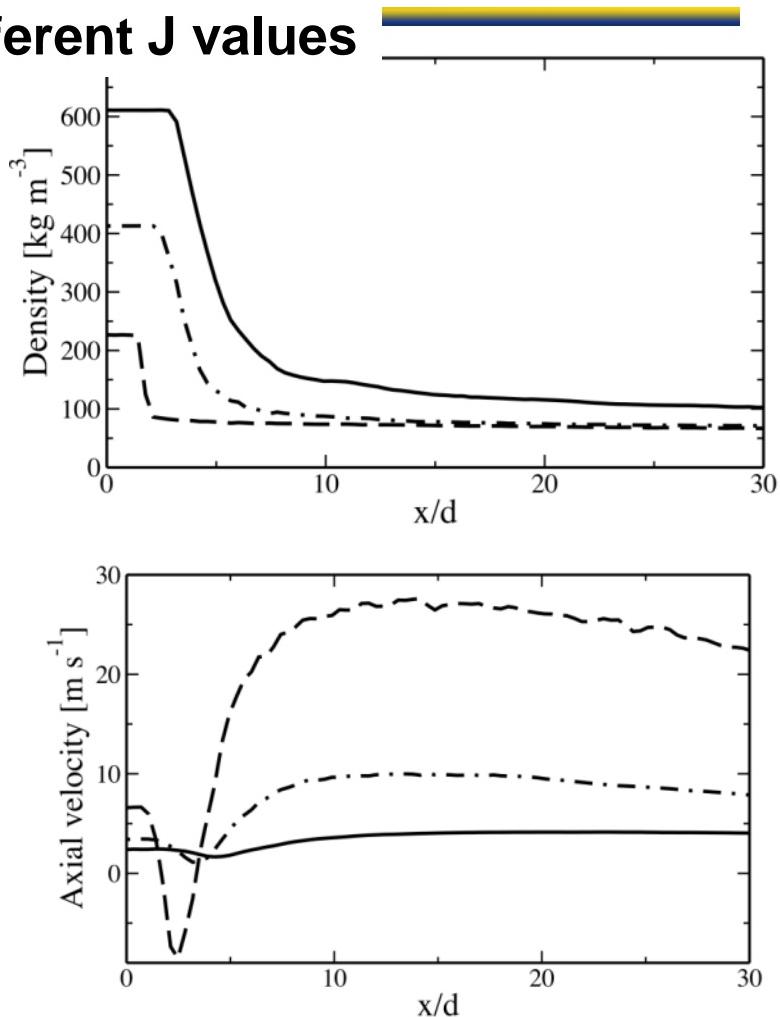
PAN



Velocity Fields for Different J values



Longitudinal slice of axial velocity. White: minimum; black: maximum.
 Dark line indicates iso-contour of zero axial velocity. Top: $J = 1.1$; middle: $J = 3.0$; bottom: $J = 9.3$.



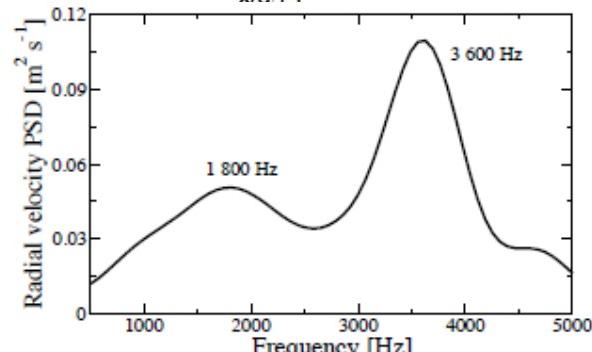
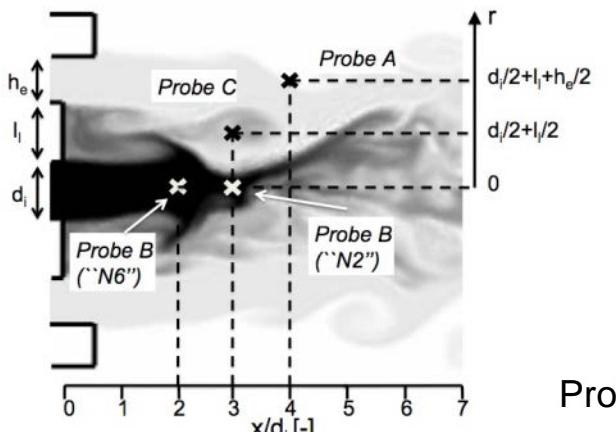
Top: centerline profile of density; bottom:
 centerline profile of velocity. Dark line: $J = 1.1$; dash point line: $J = 3.0$; dashed line: $J = 9.3$.



Fundamental frequencies for baseline conditions

30

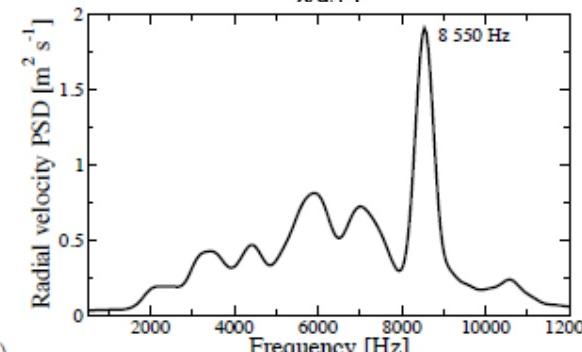
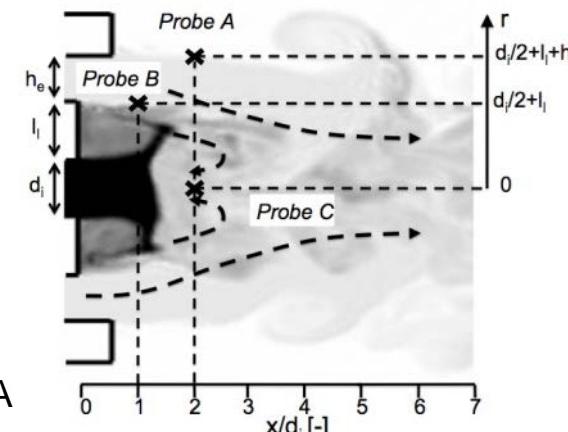
Case “N6”
 $(J=3.05)$
Density distribution
 (white: 60 kg/m³;
 black: 410 kg/m³;
 logarithmic scale).



Probe A

Case	$St^e = h_e f / U_{oj}$ (probe A)	$St^i = d_i f / U_{ij}$ (probe B)	$St^l = l_i f / U_{oj}$ (probe C)
N2	0.25	0.34	0.15
N6	0.25	0.26	0.14

Case “N8”
 $(J = 9.3)$
Density distribution
 (white: 60 kg/m³; black: maximum; logarithmic scale).



OUTER JET
 $J=3.05$
 $R=4.18$

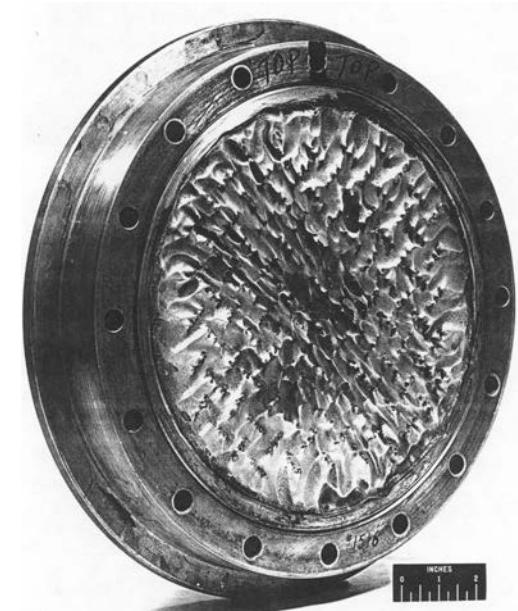
OUTER JET
 $J=1.05$
 $R=2.48$

Found relevant St numbers for our configurations

Combustion Instability Lab - Background

31

- Combustion instability is an unsustainable growth of pressure and heat transfer fluctuations in a rocket engine
 - Irreparable damage can occur in <1s
- Combustion Instability caused a 4-yr delay in the development of the F-1 engine used in the Apollo program
 - More than \$400M for the propellants alone at 2010 prices
 - More than 2000 full scale test



Damaged F-1 engine injector faceplate caused by combustion instabilities

“Combustion instabilities have been observed in almost every engine development effort, including even the most recent development programs” – current JANNAF Stability Panel Draft

AFOSR/NASA Combustion Stability Workshop, July 8-11 2008

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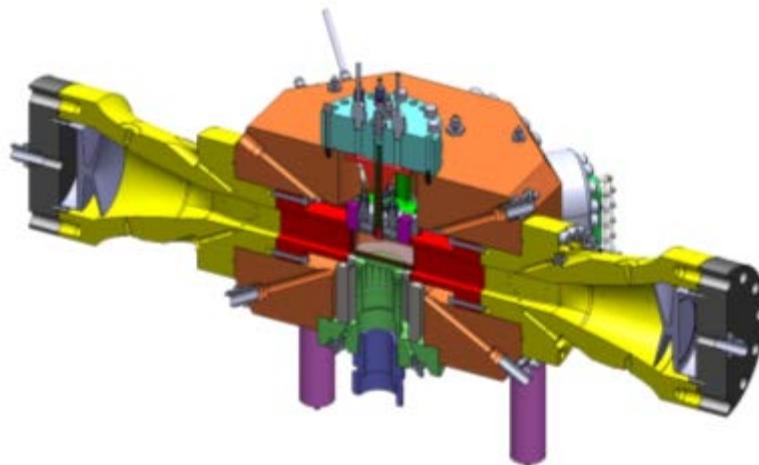
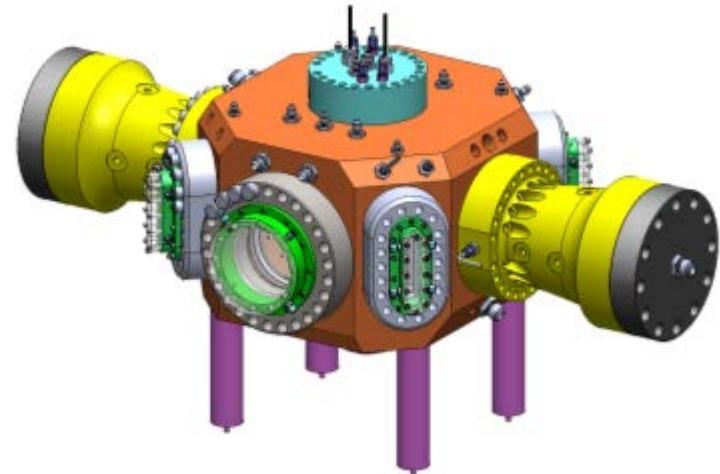
- The single largest unknown in combustion instability is the “combustion response” (how combustion responds to acoustic waves)
- Within the combustion response, flame holding in the near injector field is a key mechanism
- GA Tech was selected to lead an effort on a closed-loop study.



EC-4H – Combustion Instability Lab

33

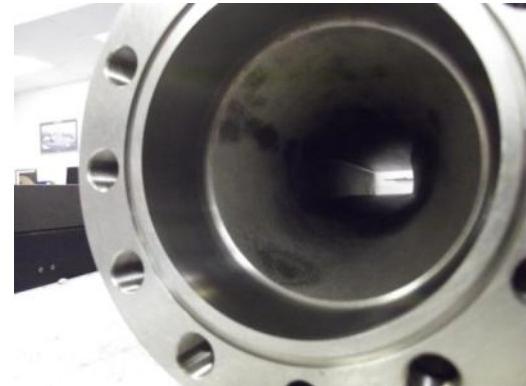
- Concentrate on near injector field
- Measure p' and q' simultaneously to evaluate the Rayleigh criteria for combustion instability
- Start with shear coaxial jets – cold flow heritage
- Lab designed for 2000 psi – about double the pressure from other labs in the world
- Start with current design for acoustic drivers pressure nodes and antinodes



Status

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- 1500 g LN₂ tank installed Sept 28, 2011
- Installed Class I Div 2 outlets (115V, 208V, 240V) – stripped floor for O₂ compatibility
- First chamber pieces arrived week of March 5, 2012
- Fluid systems in full construction



Conclusions

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- Mixing for shear coaxial jets has other major variables other than momentum flux ratio (J)
 - Ratio of inner jet temperatures is another important variable
 - Geometry – Area ratio and lip thickness also affect mixing
- For LARthick
 - Found bending mode with largest effect at velocity antinodes
 - The reduction on the dark core length was greatest for a medium J range
 - For near critical pressures, the collaboration with ECP determined relevant St for our injector configuration and was able to capture qualitative behavior of natural and excited jets
- For SARthin
 - Did not see bending mode for conditions studied
 - Saw vortex roll-up and puffing occurring over entire J range (0.09-21) tested –
 - PAN forcing produced symmetric flow structures regardless of J
 - Spectral plots showed strong response to PAN forcing at low and high J
- For LARthin
 - Sees both bending and vortex roll-up modes depending on the acoustic frequency
 - PAN forcing at low J produced symmetric flow structures, while at higher J , influence of forcing subsided

Spectral magnitude plots showed decreasing influence of PAN forcing with increasing J



BACKUP MATERIAL



Distribution A: Approved for Public Release; Distribution Unlimited

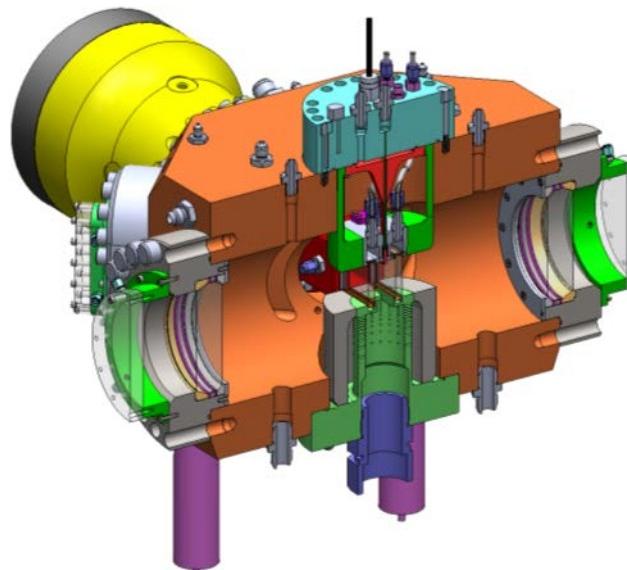
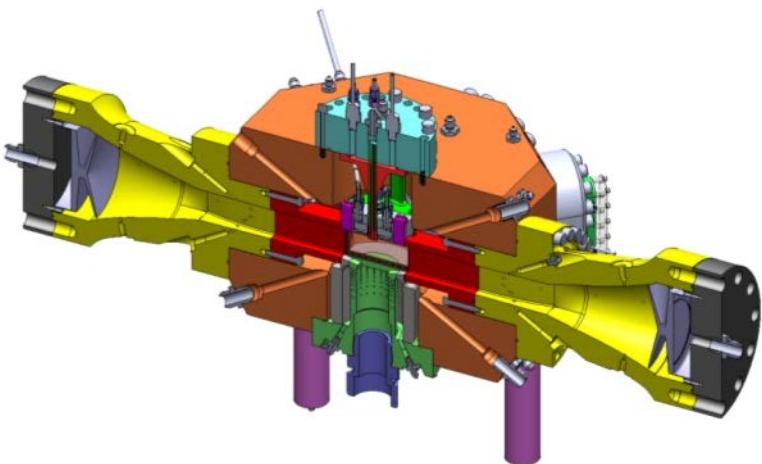
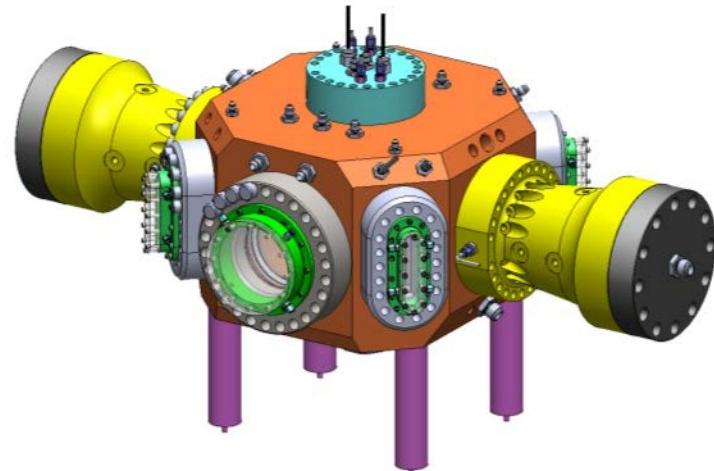


New Combustion Chamber

37

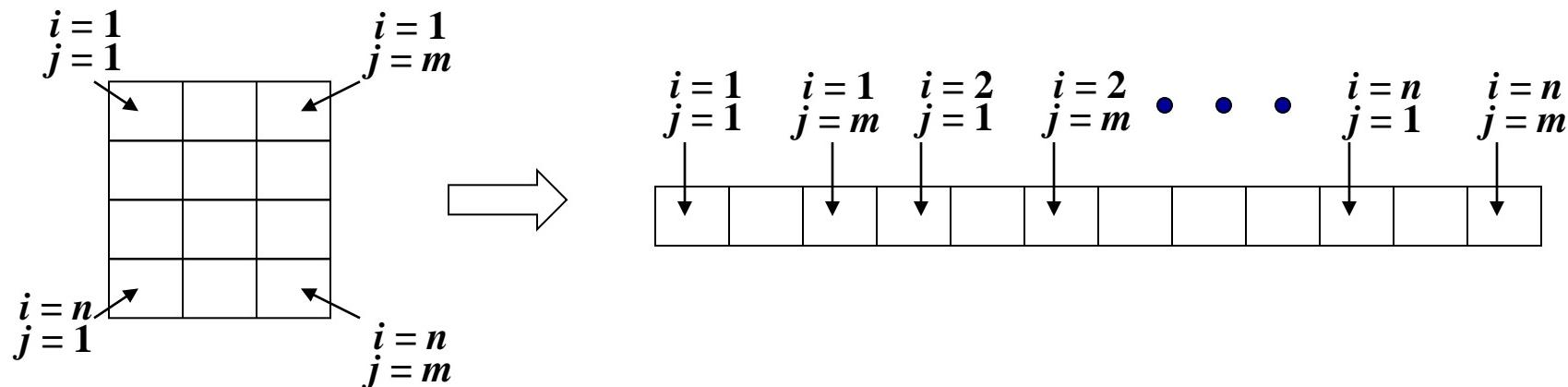
AFRL – Edwards was tasked to develop an experiment and to lead a joint experimental / modeling team to study coupled flame holding mechanisms.

LEVERAGE EXPERIENCE
GAINED WITH COLD FLOW
EXPERIMENTS

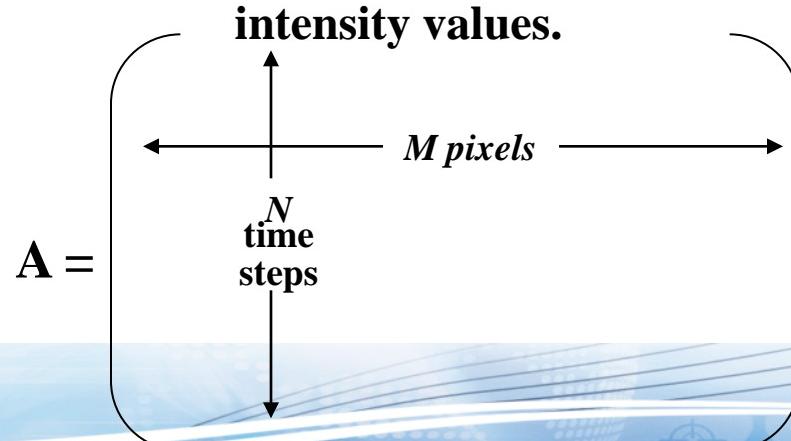


Construction and Organization of Data Set

- First, form a row vector consisting of all pixel intensity values of each snapshot image (with resolution of n rows by m columns) in order of increasing columns, then increasing rows



- Then, combine all such row vectors for N sequences of image frames resulting in a matrix A consisting of N rows by ($M = n \times m$) columns of intensity values.



Matrix Decomposition

- Eigenvalue decomposition or singular value decomposition (SVD) can be used
- SVD Subroutine readily available in MATLAB®
- Prior to matrix decomposition, the temporal mean of A was subtracted resulting in a matrix of intensity fluctuations \tilde{A} , i.e.,

$$\tilde{A}_{ij} = A_{ij} - \frac{1}{N} \sum_i A_{ij} \quad \begin{matrix} \text{for } i = 1 \dots N, \\ j = 1 \dots M \end{matrix}$$

- Application of SVD on \tilde{A} gives two orthogonal matrices U (NxN) and V (MxM), and a diagonal matrix S (NxM) of singular values in increasing order of magnitude

$$\tilde{A} = USV^T = QV^T$$

- Thus, a time-resolved set of images intensity fluctuations $\tilde{A}(x,t)$ can be represented as a linear combination of orthonormal basis functions ϕ_k such that

$$\tilde{A}(x,t) = \sum_{k=1}^M a_k(t) \phi_k(x)$$

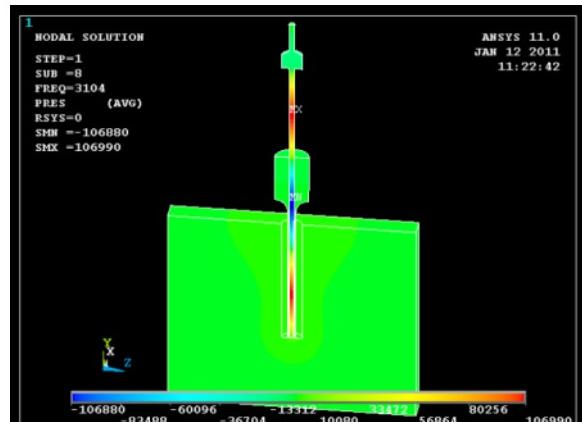
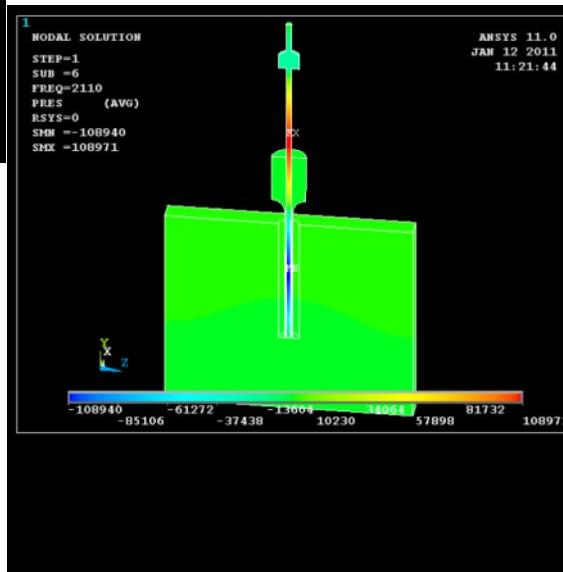
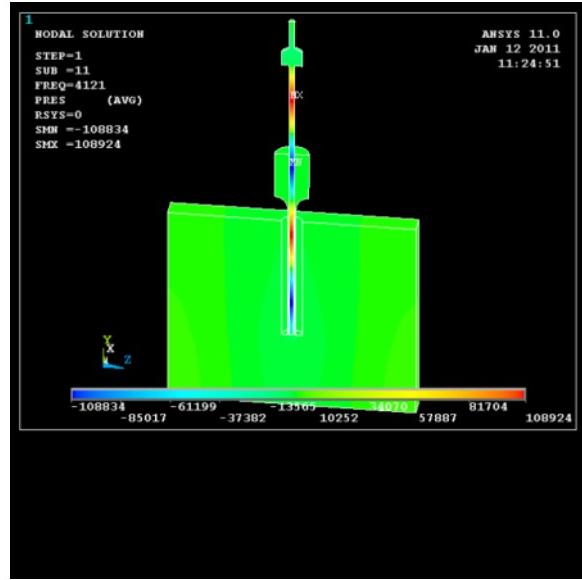
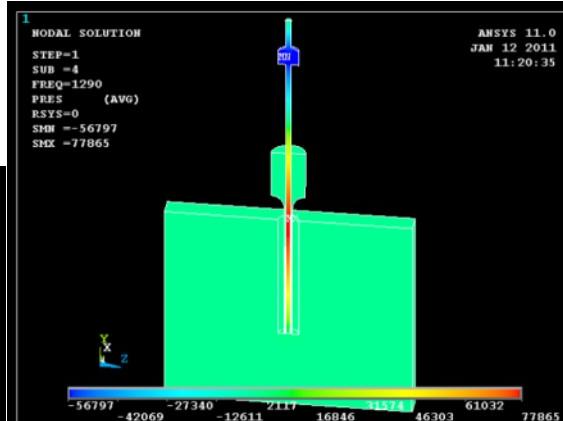
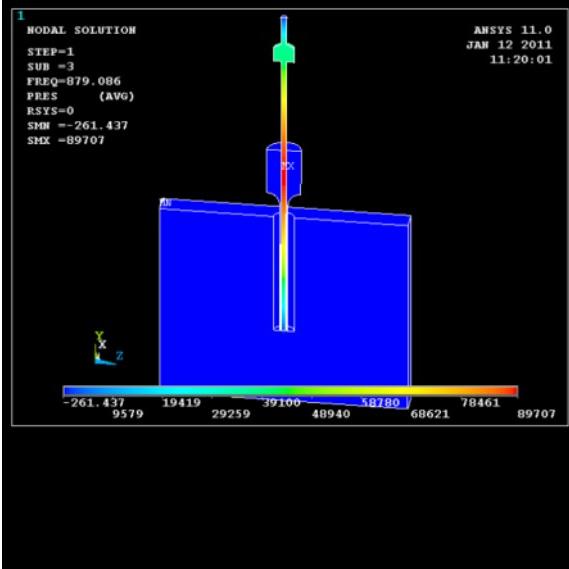
where $a_k(t)$ are time dependent orthonormal amplitude coefficients and $\phi_k(x)$ are the proper orthogonal modes of \tilde{A} .

- Equivlance: columns of Q ~ $a_k(t)$, columns of V ~ $\phi_k(x)$

Acoustic Analysis for Injectors

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In collaboration
with Jeff Muss and
Rory Davis, Sierra
Engineering



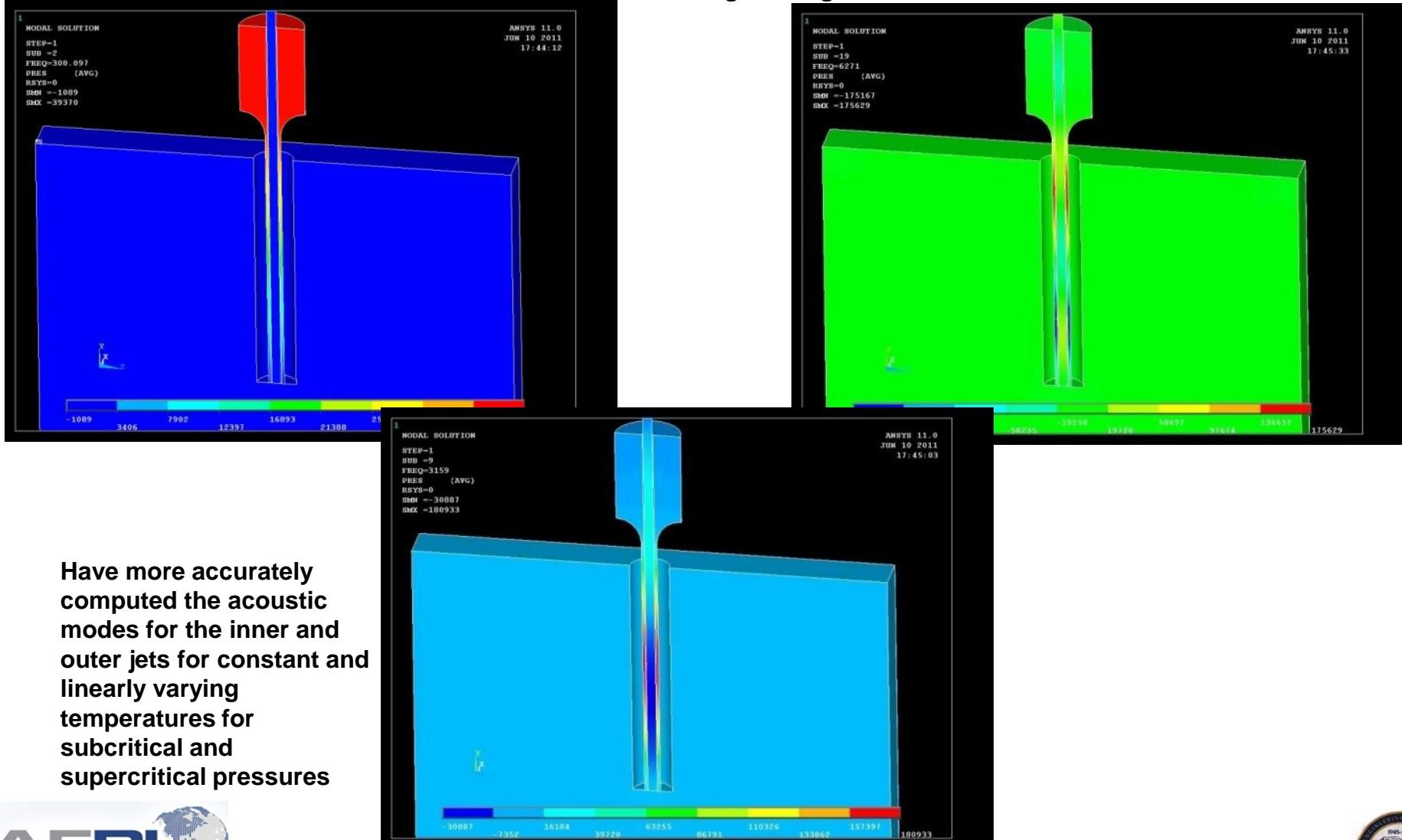
Have more accurately
computed the acoustic
modes for the inner and
outer jets for constant and
linearly varying
temperatures for
subcritical and
supercritical pressures



Acoustic Analysis for Injectors

41

In collaboration with Jeff Muss and Rory Davis, Sierra Engineering



Have more accurately computed the acoustic modes for the inner and outer jets for constant and linearly varying temperatures for subcritical and supercritical pressures



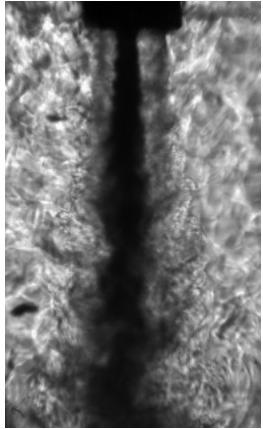
Distribution A: Approved for Public Release; Distribution Unlimited



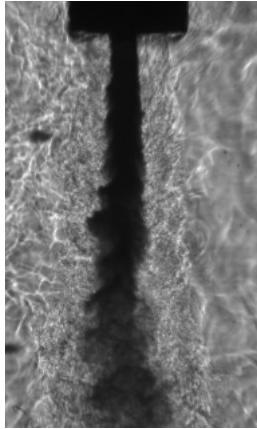
Effect of R on L/D for a given J

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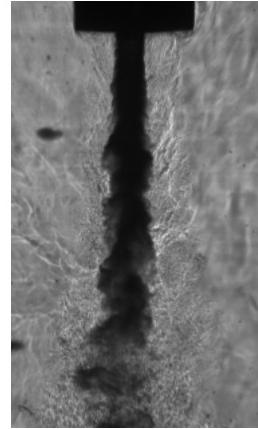
Injector IV: Constant J , Varying R



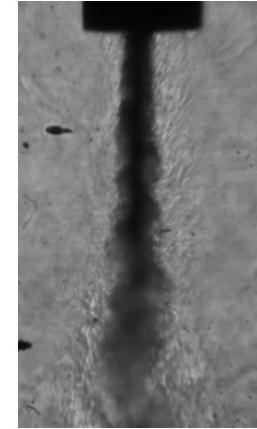
$J = 2.0$
 $R = 3.0$
 $L/D_1 = 17.9$



$J = 2.0$
 $R = 3.5$
 $L/D_1 = 12.1$

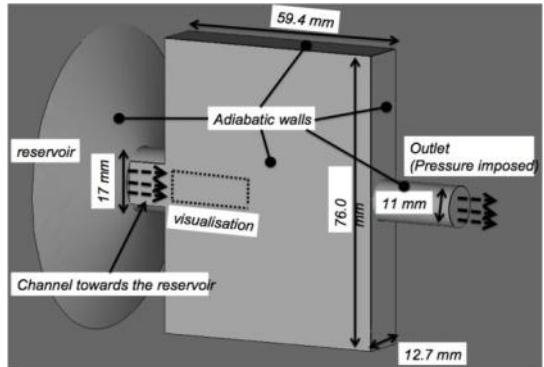


$J = 2.0$
 $R = 4.0$
 $L/D_1 = 11.6$

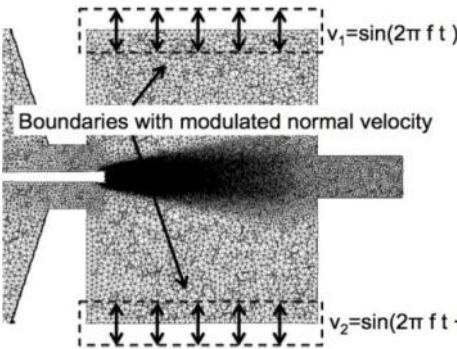


$J = 2.1$
 $R = 4.3$
 $L/D_1 = 10.1$

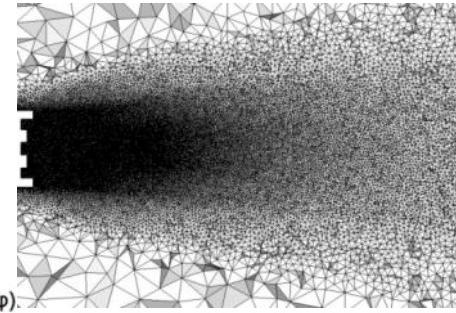
Collaboration with ECP: Grid and Mesh



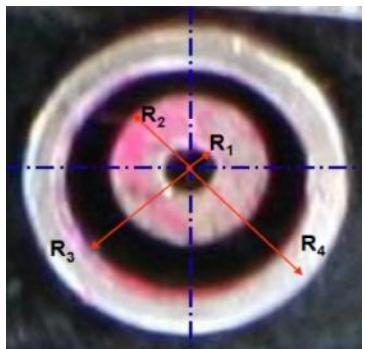
3D visualization of reservoir



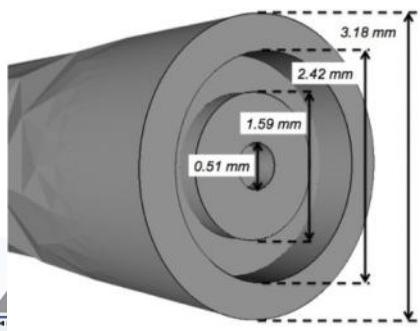
Longitudinal cut of domain with the BC's



Mesh detail near the injector



Experimental Injector



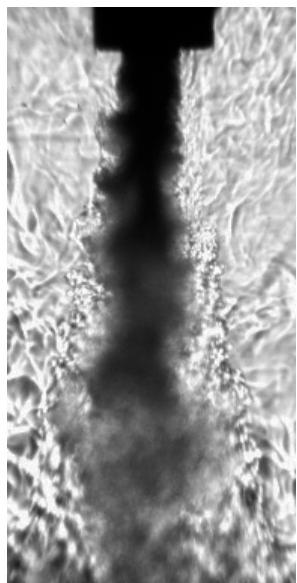
CFD Injector

- **Solver: AVBP – state of the art LES code**
 - With real fluid properties to tackle supercritical fluids
- **Mesh: 2 100 000 nodes/10 000 000 tetrahedra**
 - Highly refined near the injector (0.032 mm on a distance of 10 inner jet diameters)
- **CPU hours on Europe SuperComputer Center: 100,000**

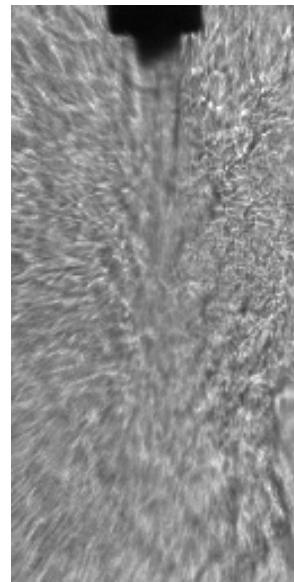


Effect of Temperature on L/D for a given J

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**J = 9.4 R=9.9
109K/203K
Ui=0.93/9.2m/s
SAR_thinLip**



**J = 9.4 R=9.9
128K/192K
Ui=6.6 /36.2m/s
LAR_thickLip**

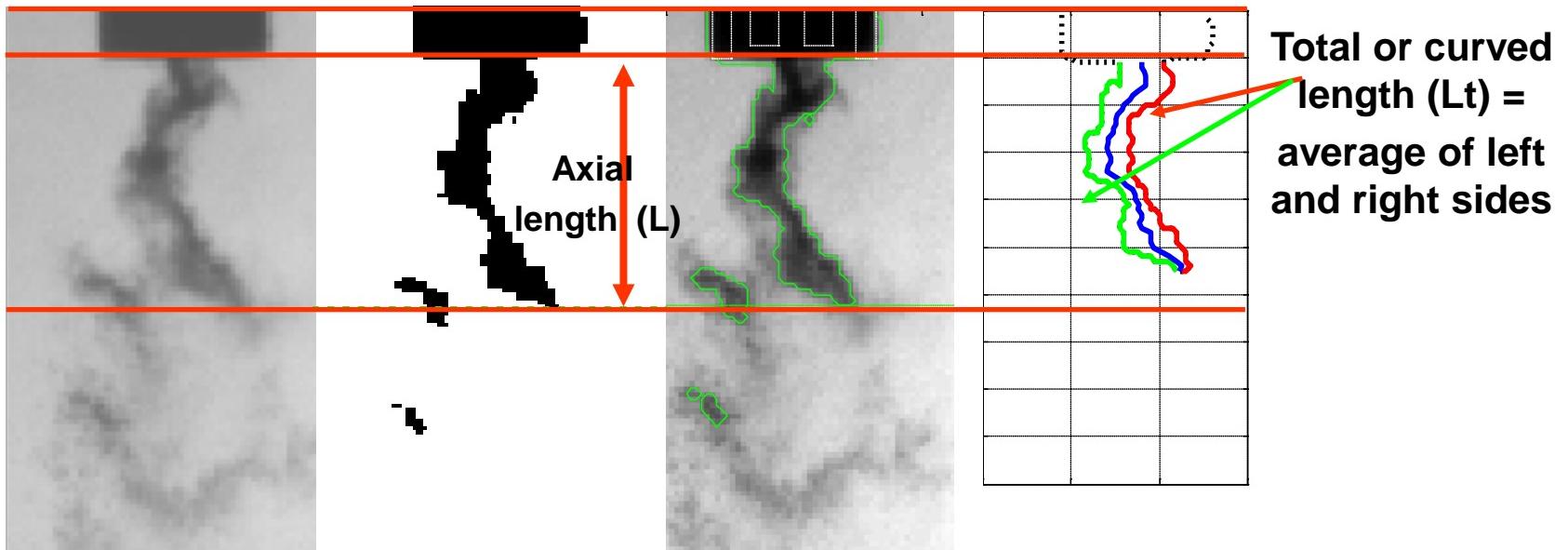
Flow Structure Comparison

	Date & Case	F _f (kHz)	P _c (MPa)	T _{outer} (K)	T _{inner} (K)	u _{outer} (m/s)	u _{inner} (m/s)	density ratio	VR	J	oj mode match	P' _{center} /P _c (%)	P' _{inner} /P' _{center} (%)	P' _{outer} /P' _{center} (%)	Structure Type	
Graham Recess = 0																
SbC1	04May09 c1	3.04	1.49	207	106	1.4	0.87	0.036	1.5	0.09	Y up	0.68	13.47	187.21	large ij vortex roll up (puffs), intermitent penetration of ij	
SbC2	04May09 c2	2.96	1.5	187	110	2.7	0.97	0.045	2.8	0.35	Y dwn	0.64	10.16	198.53	med ij vortex roll up at ~3000 Hz, no penetration of ij	
SbC3	23April09 c2	2.96	1.5	150	106	5.6	0.94	0.057	5.8	2.02	Y up	1.06	21.24	60.55	large ij vortex roll up at ~2857 Hz	
SbC7	22April09 c1	3.04	1.49	188	110	14	0.98	0.045	14.2	9.00	Y up/down	0.81	3.75	61.47	large ij vortex roll up @~2857 Hz	
SbC8	23April09 c1	3.04	1.5	170	109	15	0.94	0.050	16.0	12.55	N?	1.13	3.37	55.84	large ij vortex roll up @~2857 Hz, oj flips ij vortices	
SbC9	22April09 c2	2.96	1.5	187	110	17.4	0.99	0.045	17.5	13.80	Y up	1.31	1.90	49.22	large ij vortex roll up downstream, large oj roll up at exit	
SbC10	23April09 c3	3.06	1.5	178	110	21.51	0.99	0.048	21.2	21.03	N?	0.56	13.32	5.15	med ij vortex roll up downstream	
NC1	05May09 c2	3.09	3.57	176	120	3.7	1.0	0.140	3.6	1.92	Y up	0.85	4.96	72.69	large ij vortex roll up, pinched off	
NC2	05May09 c3	3.06	3.57	186	122	5.7	1.2	0.136	5.2	3.07	Y up/down	0.66	2.36	64.30	large ij vortex roll up	
NC3	30Apr09 c1	3.02	3.58	209	112	6.1	1.0	0.097	6.9	3.92	N	0.20	14.63	30.67	minimal ij disturbance	
NC4	27Apr09 c2	2.98	3.57	181	112	9	0.98	0.118	9.2	9.92	Y up/down	0.33	5.29	96.91	large ij vortex roll up	
NC5	27Apr09 c3	3.05	3.57	183	113	13	0.98	0.118	13.0	20.69	Y up	0.31	13.95	51.82	large ij vortex roll up downstream	
Rodriguez Recess = 0.5D_t																
SbC1	06Nov08 c1	3.01	1.48	199	105	1.4	0.9	0.040	1.5	0.09	Y dwn	0.38	3.29	326.90	large ij vortex roll up (puffs), intact core flow	
SbC2	07Nov08 c1	2.96	1.49	197	106	3	0.9	0.039	3.3	0.43	Y dwn	0.62	4.70	155.04	large ij vortex roll up (puffs), no intact core	
SbC3	10Nov08 c1	2.97	1.49	195	109	6.6	1.0	0.042	6.9	2.00	Y up/down	0.58	3.77	117.85	large ij vortex roll up	
SbC4	10Nov08 c2	3.04	1.49	189	110	8.5	0.97	0.045	8.7	3.40	Y up/down	0.85	1.40	65.43	large ij vortex roll up, pinched off	
SbC5	10Nov08 c3	3.02	1.49	184	110	10	0.97	0.043	11.0	5.20	Y up/down	1.18	2.01	49.59	large ij vortex roll up	
SbC6	12Nov08 c1	2.96	1.49	193	108	13.0	0.9	0.040	14.0	7.80	Y dwn	0.61	1.18	113.90	large ij vortex roll up	
SbC7	12Nov08 c2	2.92	1.49	194	108	16	0.9	0.042	17.0	12.00	Y dwn	0.59	1.09	107.52	large ij vortex roll up	
SbC8	12Nov08 c3	2.9	1.48	201	109	20	1.0	0.041	21.0	18.00	N	0.51	4.89	102.90	large ij vortex roll up downstream	
NC1	18Nov08 c1	2.98	3.56	213	109	2.2	0.93	0.095	2.3	0.50	N	0.75	21.49	72.45	minimal ij disturbance (small pulsing)	
NC2	18Nov08 c2	3.06	3.56	209	109	3	0.93	0.095	3.2	0.97	Y up	0.35	10.69	55.31	minimal ij disturbance (small pulsing)	
NC3	30Dec08 c1	3	3.58	198	108	4.3	0.92	0.100	4.7	2.20	Y dwn	0.23	9.83	96.60	small ij shedding	
NC4	30Dec08 c3	3.11	3.58	199	109	6.3	0.93	0.102	6.7	4.60	Y up/down	0.35	5.57	105.82	med ij vortex roll up, no vortex growth	
NC5	30Dec08 c4	3.07	3.58	203	109	9.2	0.93	0.096	9.9	9.40	Y up/down	0.41	3.13	87.66	large ij vortex roll up downstream	
NC6	30Dec08 c5	3.09	3.56	207	111	13	0.95	0.097	14.0	19.00	Y dwn	0.42	2.83	88.32	med ij vortex roll up	
SpC1	30Dec08 c2	3.11	4.95	212	111	4.1	0.93	0.134	4.4	2.60	Y up	0.40	17.18	53.55	small ij vortex roll up	
Teshome Recess = D_t																
NC	23-Mar-10 c1	3.10	3.51	160	121	3.33	1.09	0.164	3.1	1.53	N	0.77	5.54	20.15	small ij vortex roll up	
NC	18-Feb-10	3.00	3.49	165	118	6.25	1.06	0.146	5.9	5.07	N	0.19	17.34	149.82	med ij vortex roll up, ij anihilation	
NC	26-Mar-10	3.05	3.52	184	129	32.97	8.50	0.389	3.9	5.86	Y up/dwn	0.69	19.31	43.52	laterally undulating jet, ejection of mass, ij vortex roll up downstream	
Teshome Recess = .05D_t																
NC	03Aug10 c1	3.09	4	3.56	158	126	2.5	2.23	0.207	1.1	0.26	N	0.60	7.93	18.18	small structures shed from the IJ at exit plane
NC	22July10 c1	3.1	3.52	148	123	3.39	1.93	0.203	1.8	0.63	N	0.31	37.60	14.59	not so organized structures shed from ij exit plane	
NC	30June10 c1	3.02	3.49	161	117	21.3	3.56	0.150	6.0	5.36	N	0.38	4.44	9.80	minimal ij disturbance	
NC	21June10 c1	3.08	3.52	191	130	4.74	1.26	0.393	3.8	5.56	Y up/dwn	0.24	42.63	35.50	large ij vortex roll up	
NC	05May10 c1	3.13	3.60	193	130	34.51	8.59	0.375	4.0	6.05	Y dwn				laterallyundulating ij disturbance	



Dark-Core Length

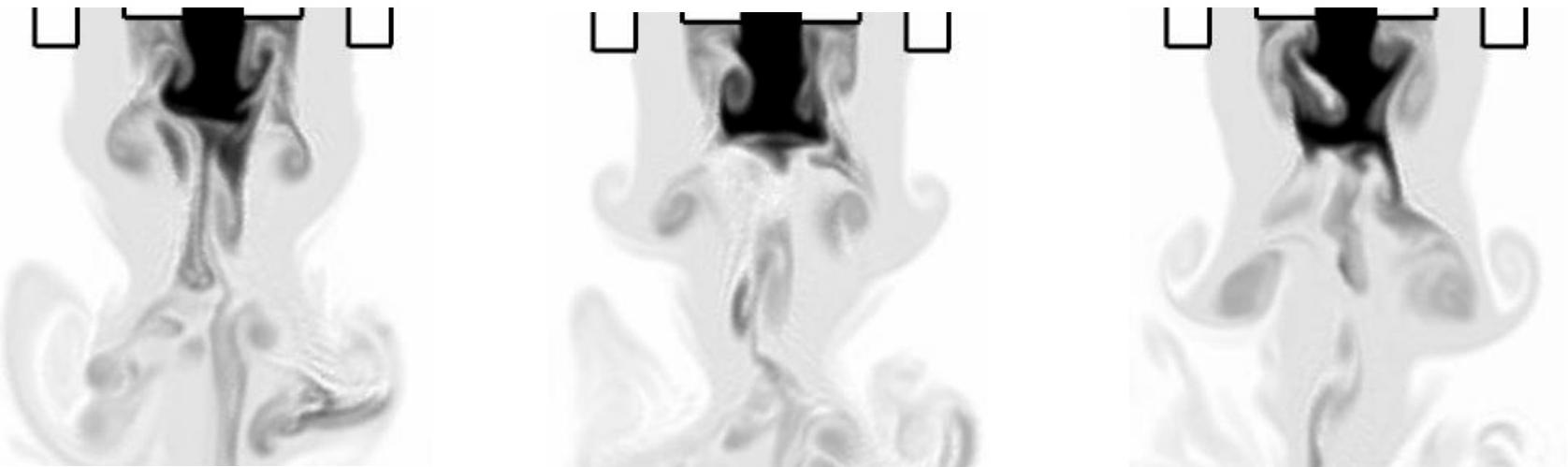
46



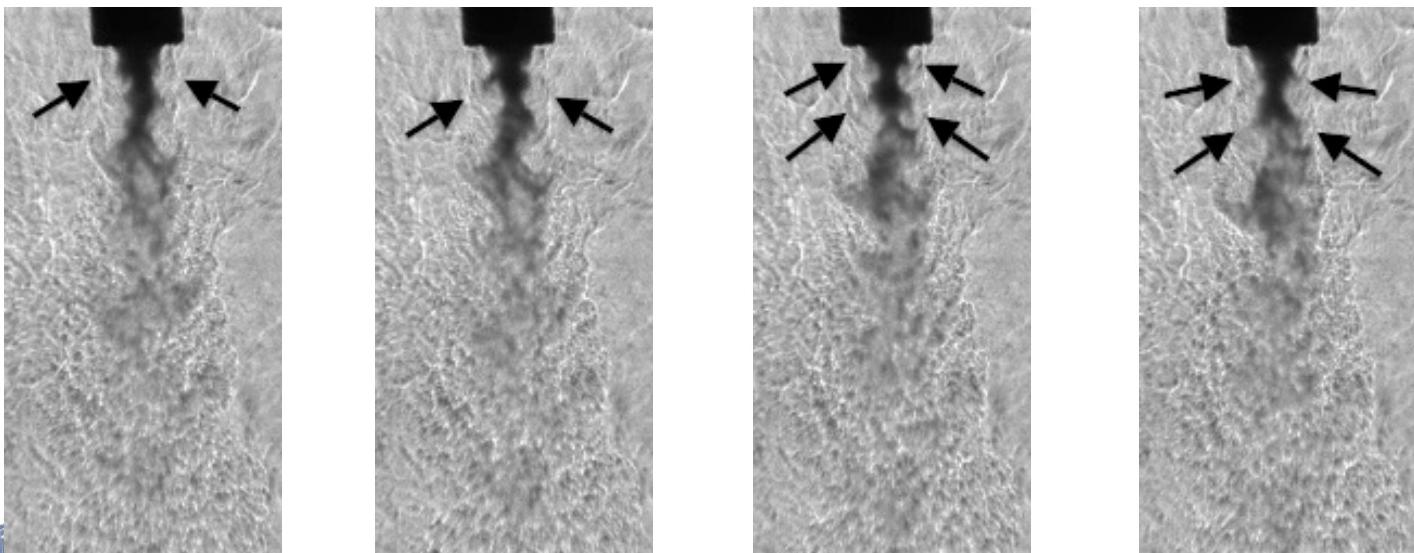
$P = 1.50 \text{ MPa}$; $P_r = 0.44$; $VR = 7.50$; $J = 2.64$; acoustic field on

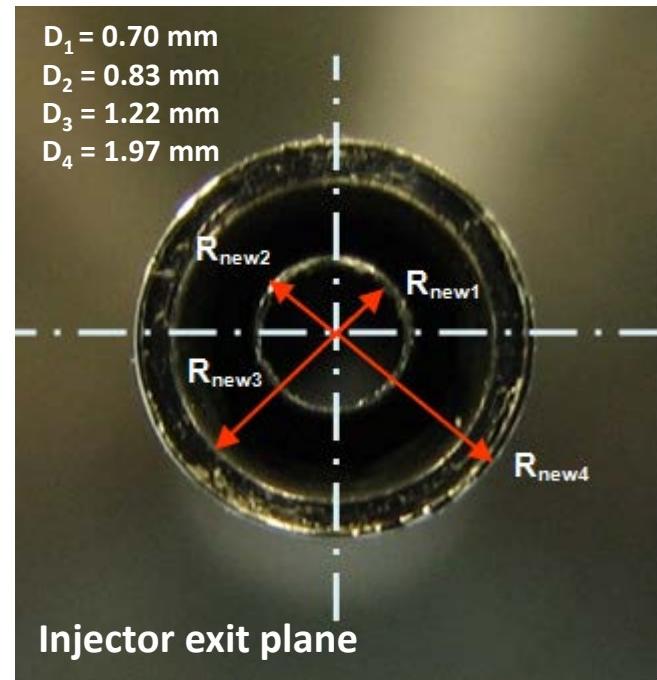
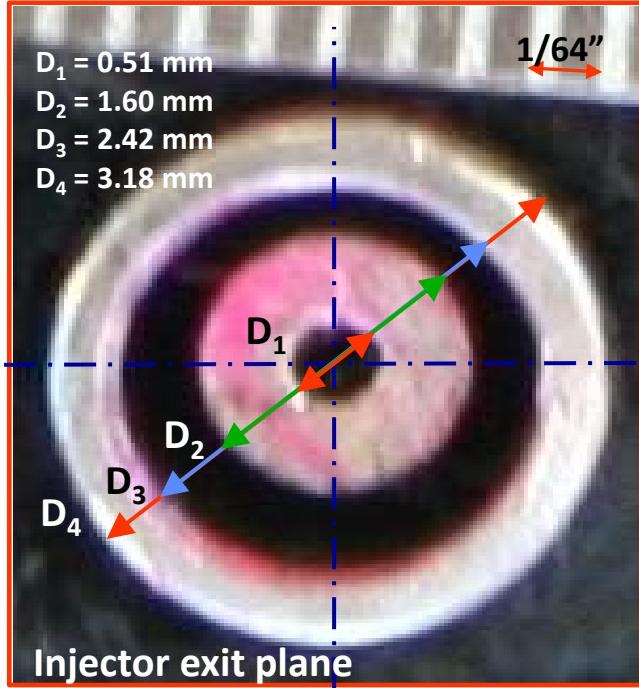
- **Threshold Images based on Otsu's method** (N. Otsu, "A Threshold Selection Method from Gray-Level Histograms," IEEE Transactions on Systems, Man, and Cybernetics, vol. 9, no. 1, pp. 62-66, 1979.)
- Accounts for variability from image to image (including d_1 the parameter by which the jet is normalized)

Acoustic Forcing Results



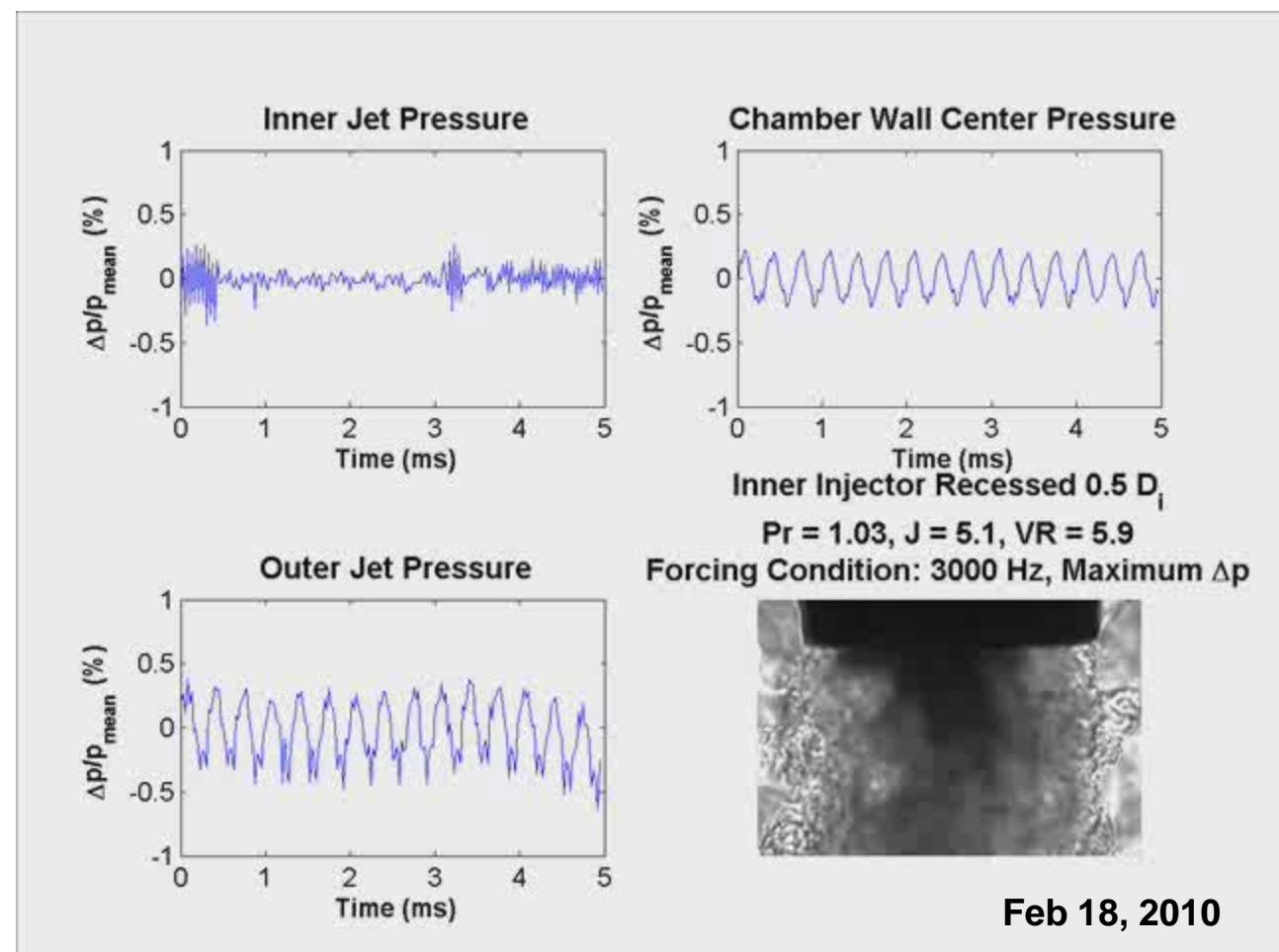
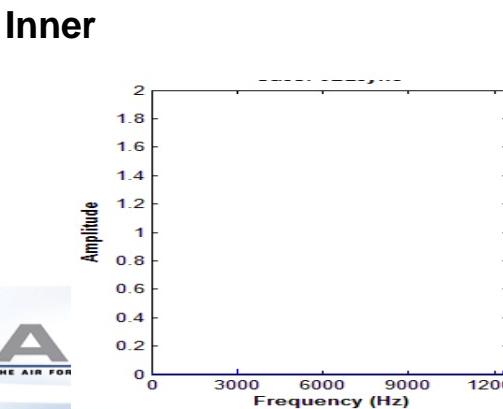
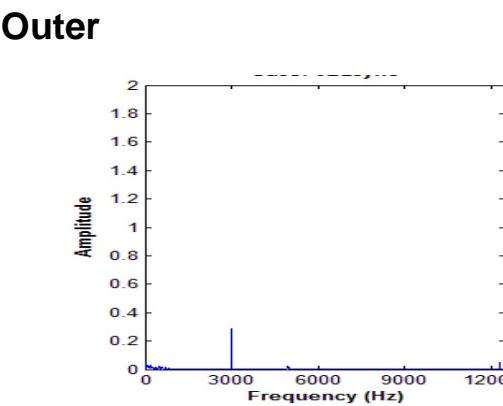
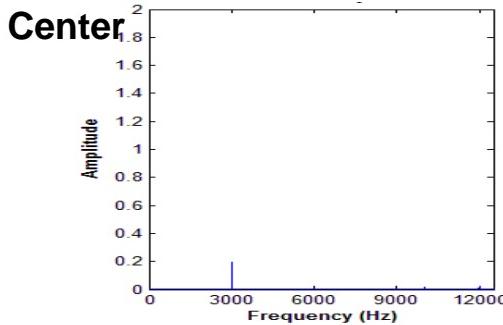
Instantaneous images of the simulation of an acoustic case with the injector at a pressure antinode for a $J = 3.0$





Synchronized p' and images: Pr=1.03, J=5.1, VR=5.9

49



Feb 18, 2010

U_o=6.25 m/s, U_i=1.06 m/s, T_o=165K , T_i=118 K

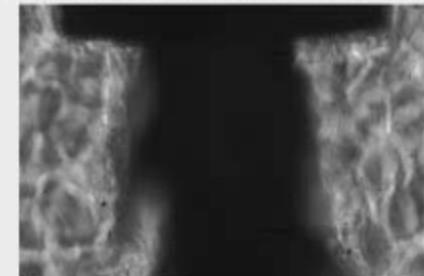
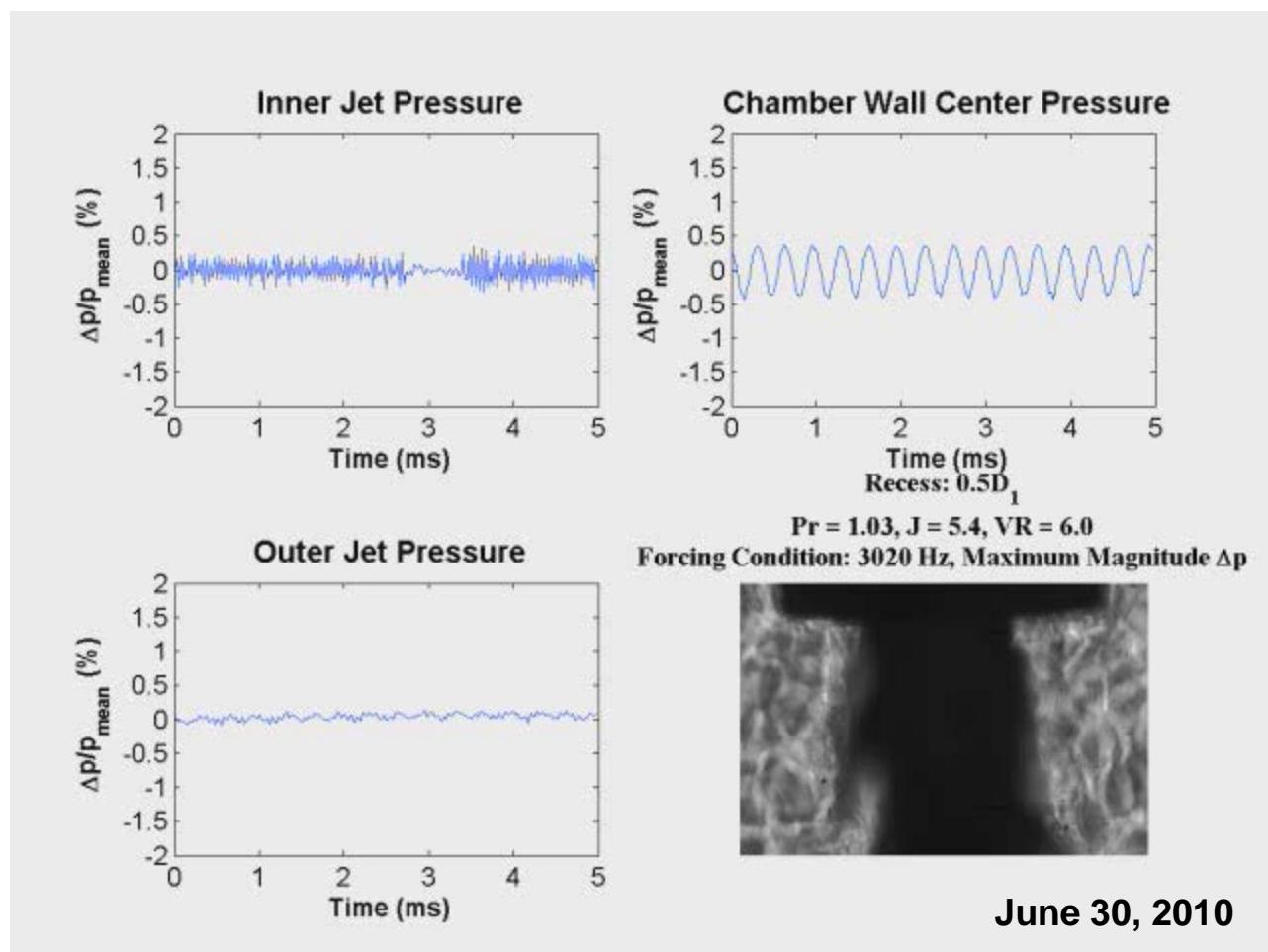
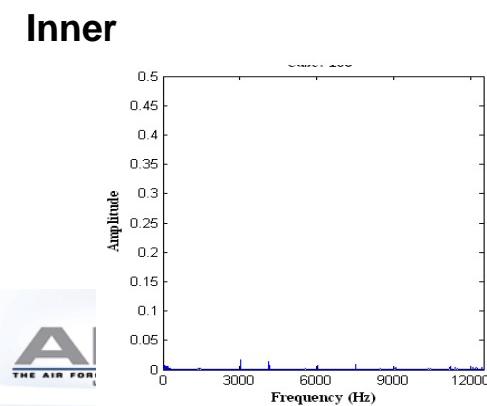
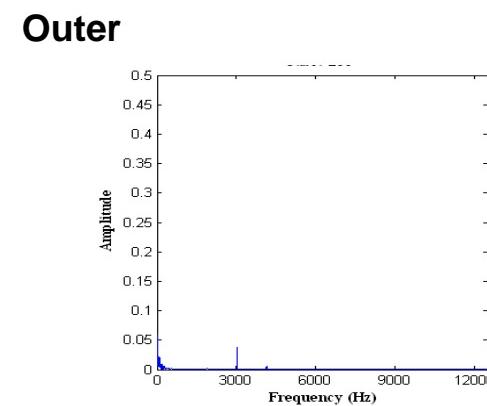
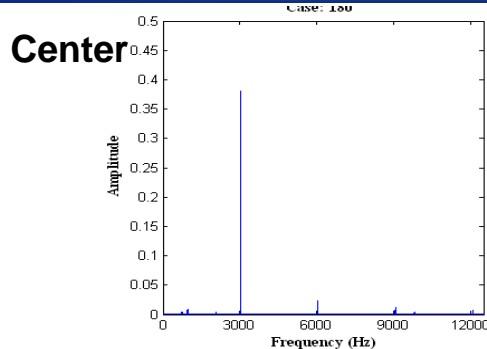
MOVIE

Distribution A: Approved for Public Release; Distribution Unlimited



Synchronized p' and images: Pr=1.03, J=5.4, VR=6.0

50



June 30, 2010

$U_o = 21.3 \text{ m/s}$, $U_i = 3.56 \text{ m/s}$, $T_o = 161 \text{ K}$, $T_i = 117 \text{ K}$

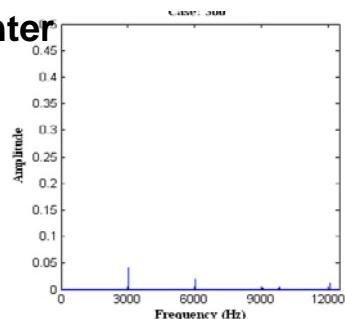
MOVIE

Distribution A: Approved for Public Release; Distribution Unlimited

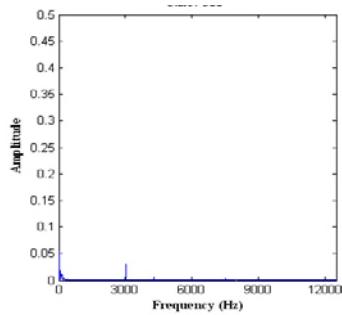


Synchronized p' and images: Pr=1.03, J=5.4, VR=6.0

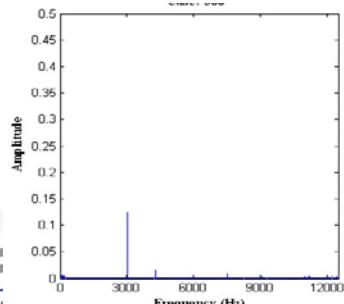
Center



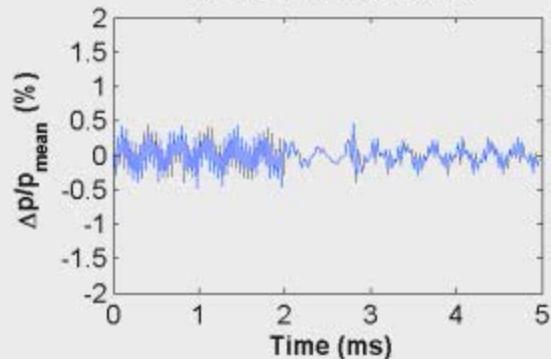
Outer



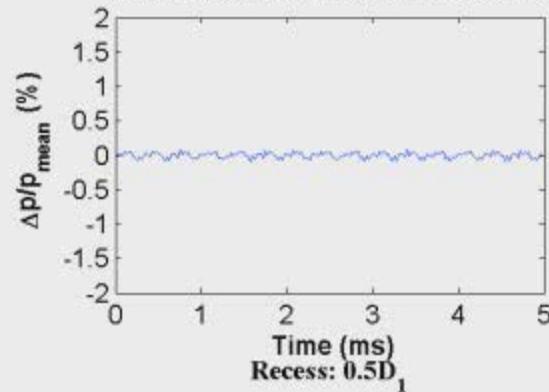
Inner



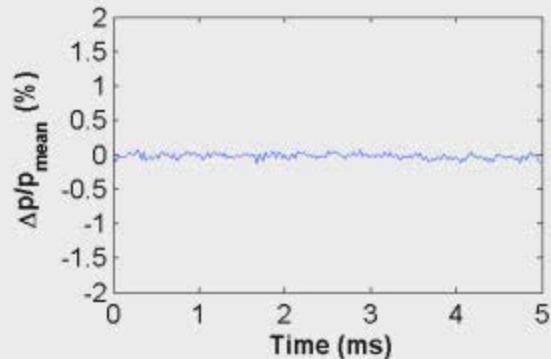
Inner Jet Pressure



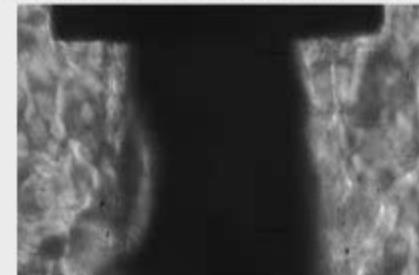
Chamber Wall Center Pressure



Outer Jet Pressure



Forcing Condition: 3020 Hz, Minimum Magnitude Δp



June 30, 2010

$U_o = 21.3 \text{ m/s}$, $U_i = 3.56 \text{ m/s}$, $T_o = 161 \text{ K}$, $T_i = 117 \text{ K}$

MOVIE

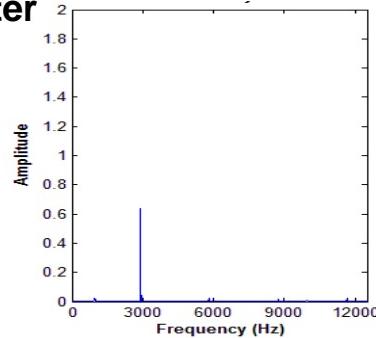
Distribution A: Approved for Public Release; Distribution Unlimited



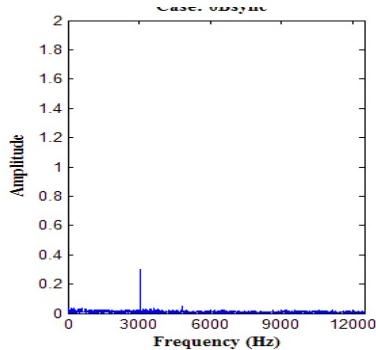
Synchronized p' and images: Pr=1.03, J=5.9, VR=3.9

52

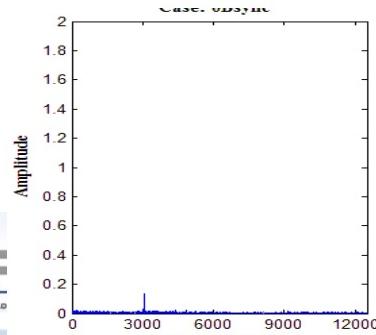
Center



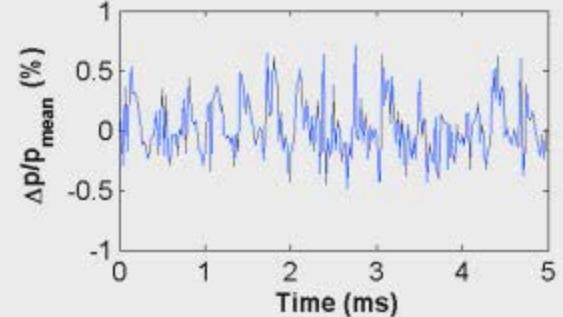
Outer



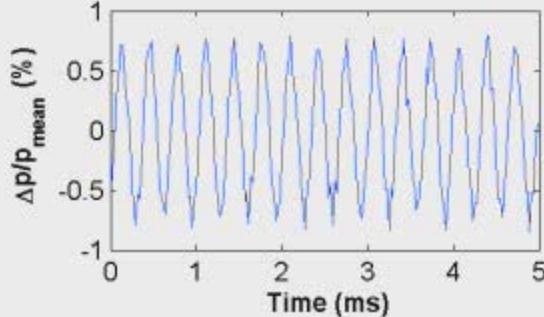
Inner



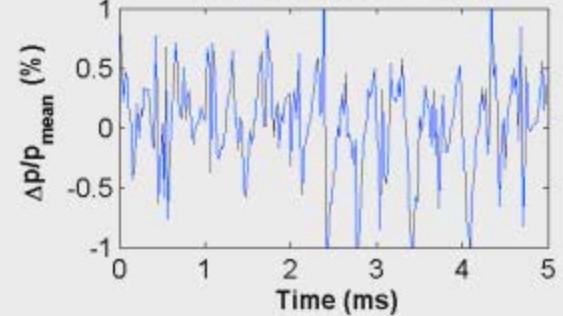
Inner Jet Pressure



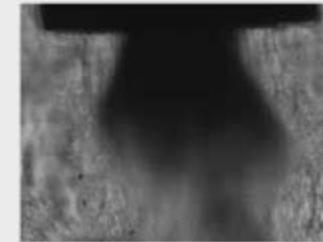
Chamber Wall Center Pressure



Outer Jet Pressure

Inner Injector Recessed 1 D_i

Pr = 1.04, J = 5.9, VR = 3.9

Forcing Condition: 3050 Hz, Maximum Δp 

March 26, 2010

U₀=33.0 m/s, U_i=8.50 m/s, T₀=184K , T_i=129 K

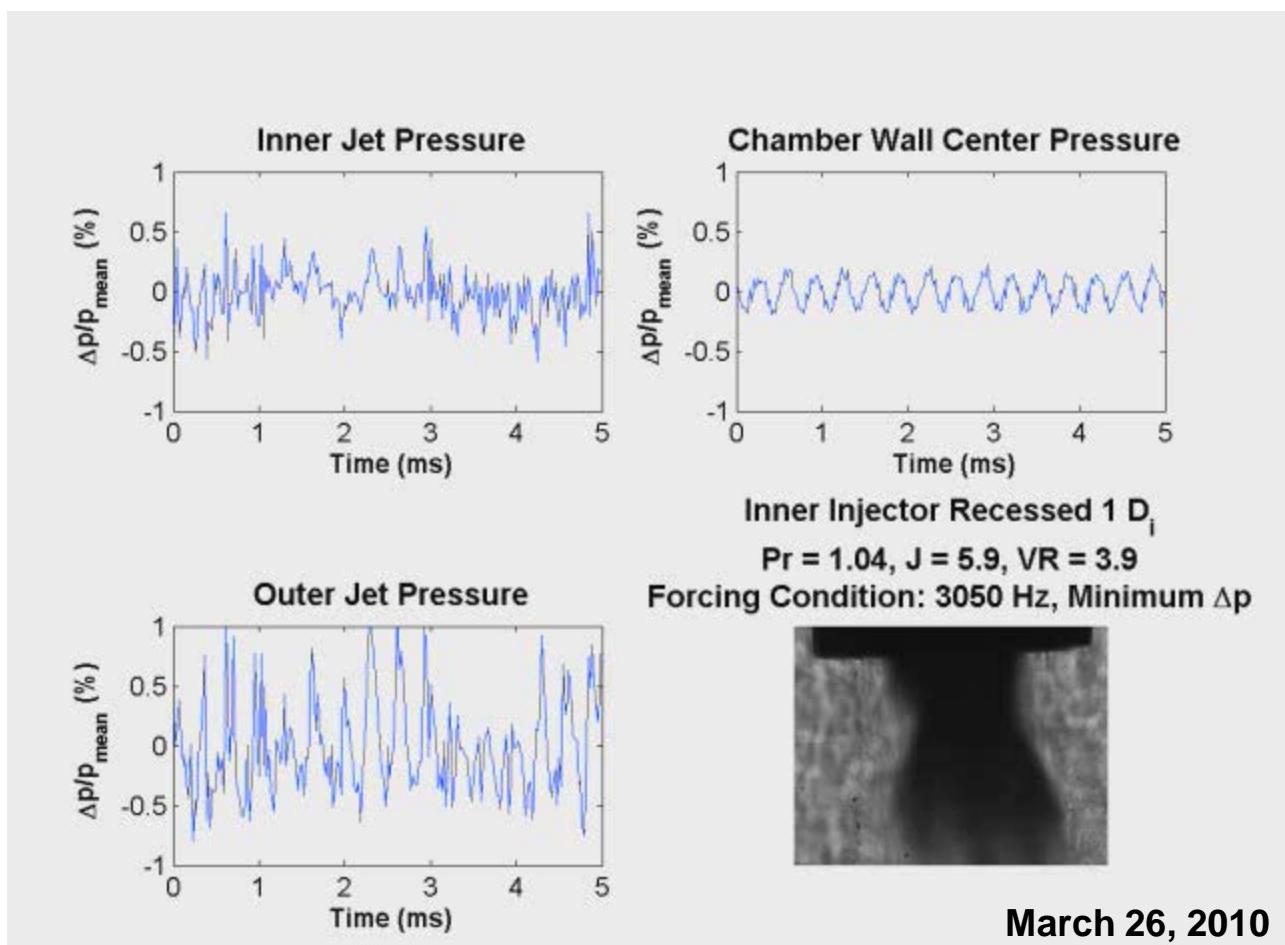
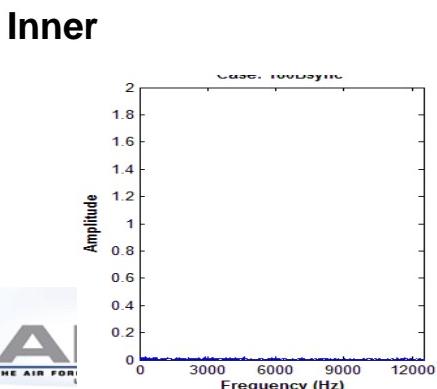
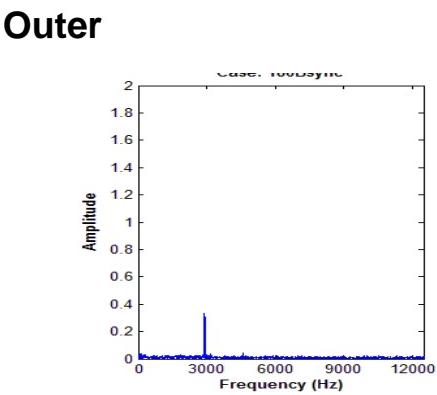
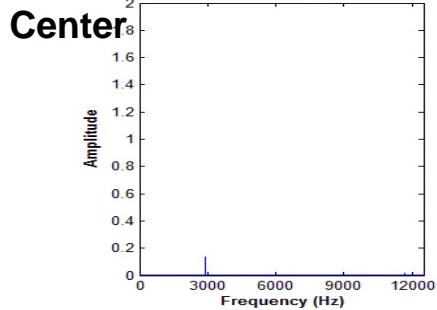
MOVIE

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Synchronized p' and images: Pr=1.03, J=5.9, VR=3.9

53



Uo=33.0 m/s, Ui=8.50 m/s, To=184K , Ti=129 K

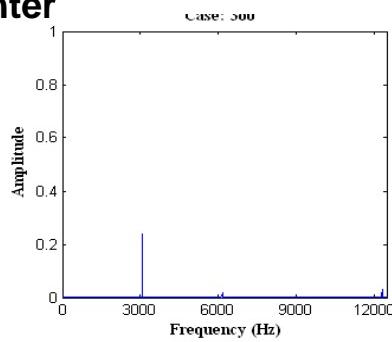
MOVIE



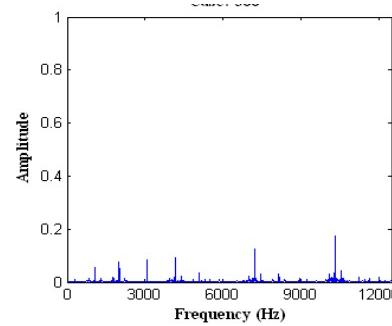
Synchronized p' and images: Pr=1.02, J=5.7, VR=3.8

54

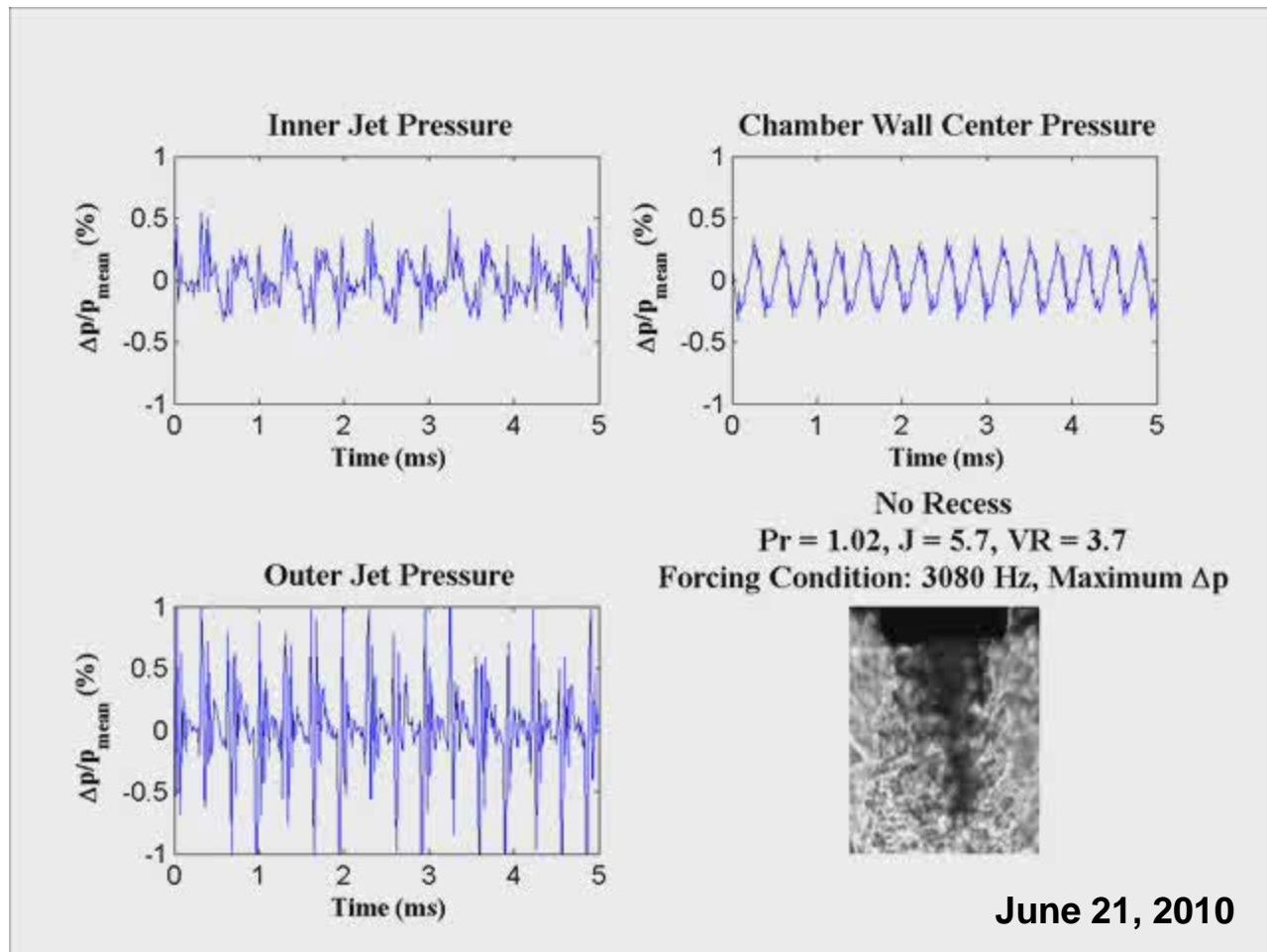
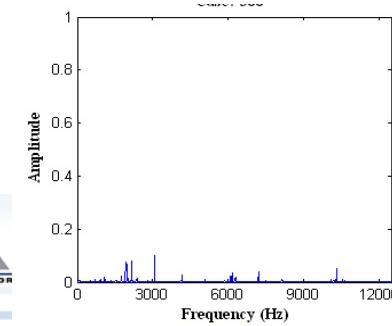
Center



Outer



Inner



June 21, 2010

$U_o = 4.74 \text{ m/s}$, $U_i = 1.26 \text{ m/s}$, $T_o = 191 \text{ K}$, $T_i = 130 \text{ K}$

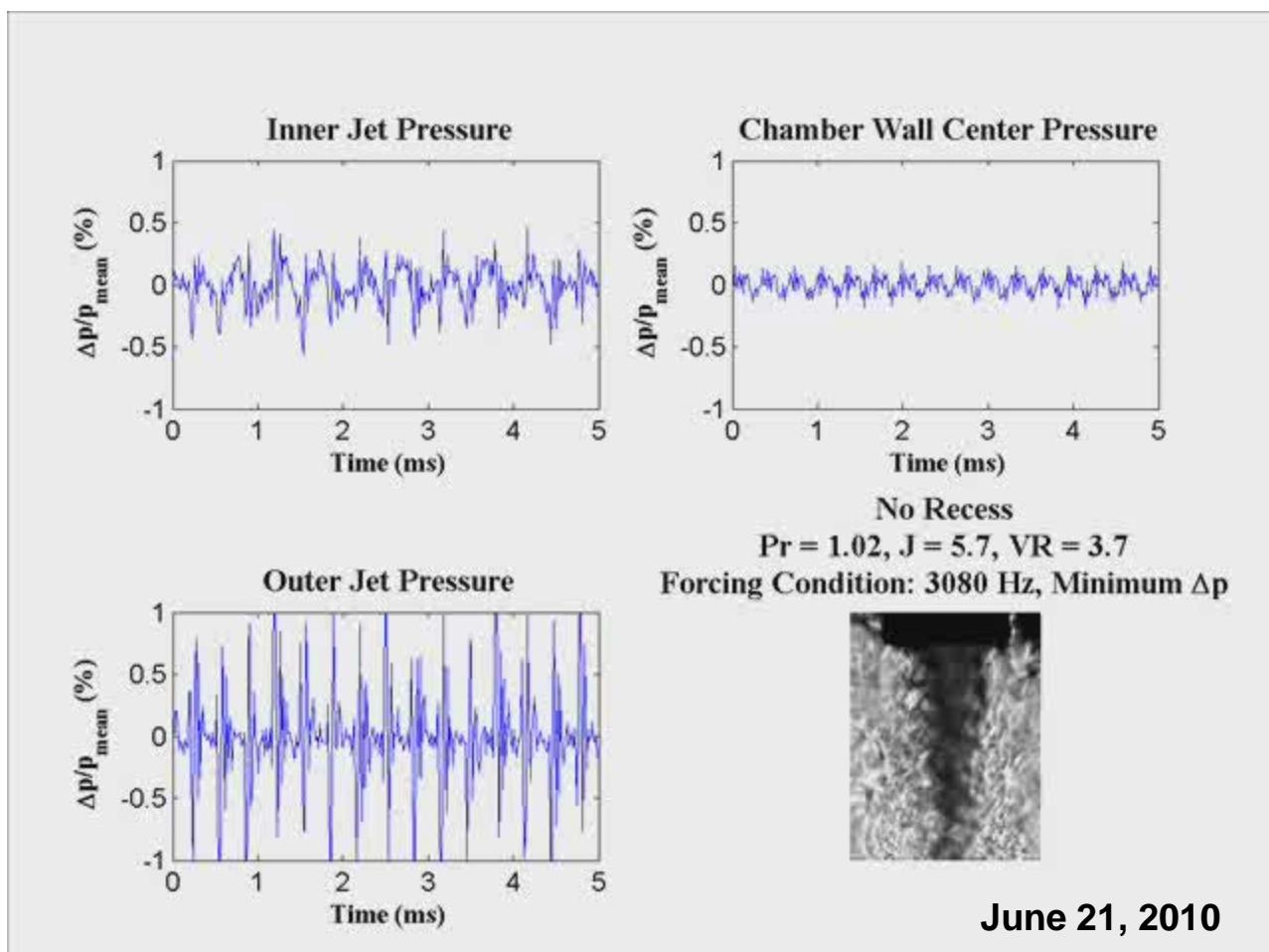
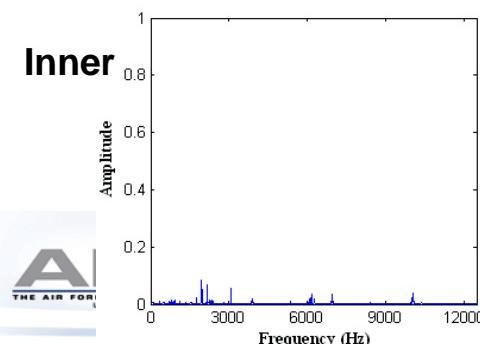
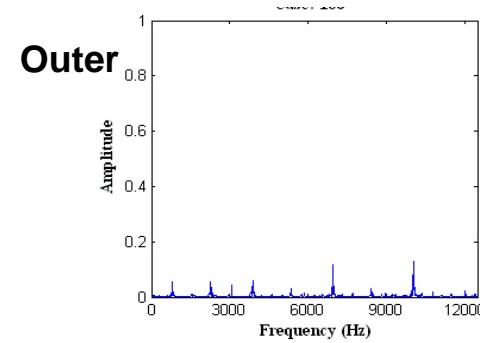
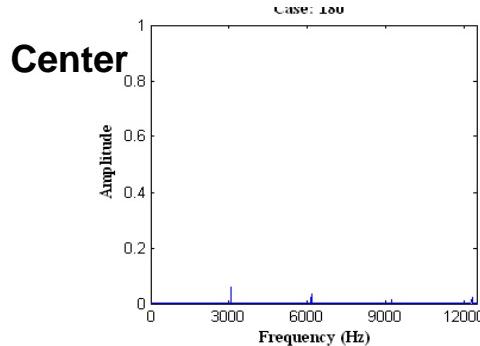
MOVIE

Distribution A: Approved for Public Release; Distribution Unlimited



Synchronized p' and images: Pr=1.02, J=5.7, VR=3.8

55



$U_o = 4.74 \text{ m/s}, U_i = 1.26 \text{ m/s}, T_o = 191 \text{ K}, T_i = 130 \text{ K}$

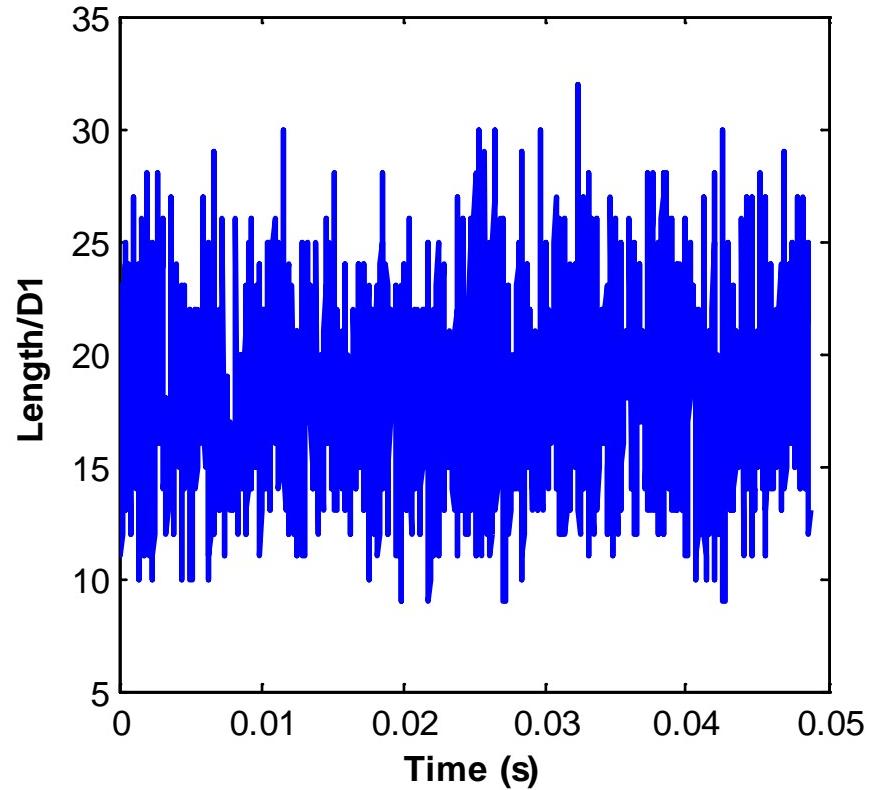
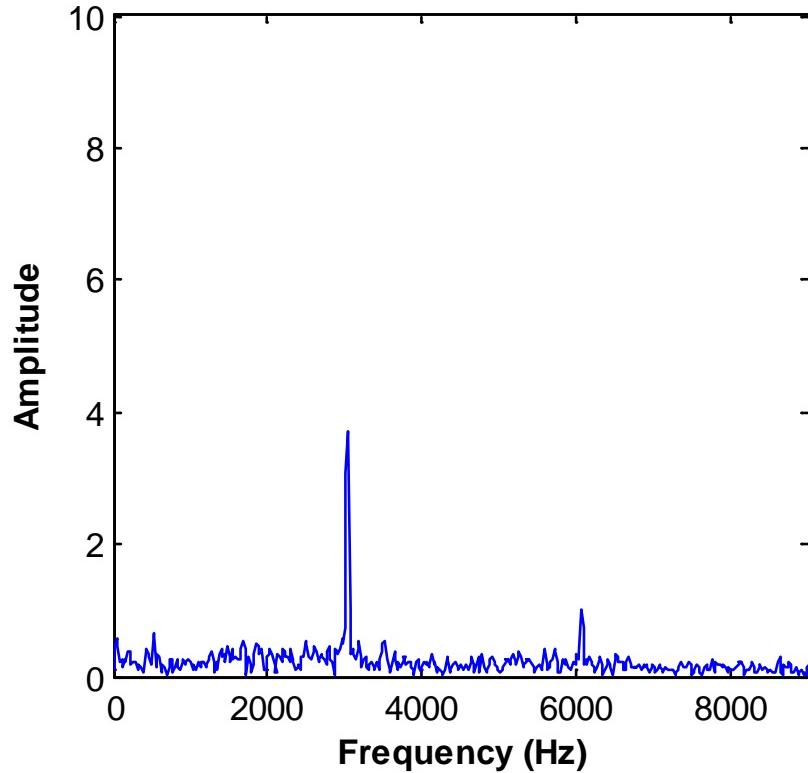
MOVIE

Distribution A: Approved for Public Release; Distribution Unlimited



Typical FFT of Dark Core Length

56



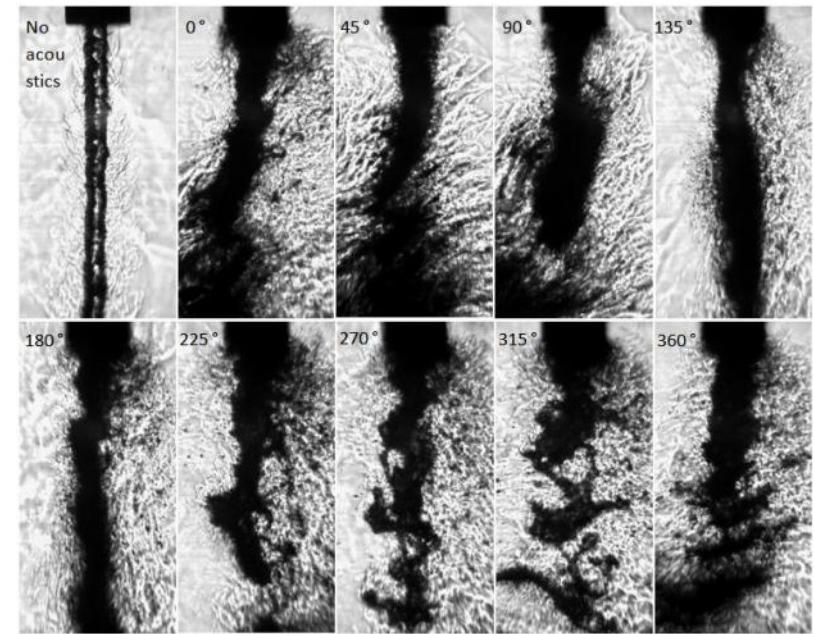
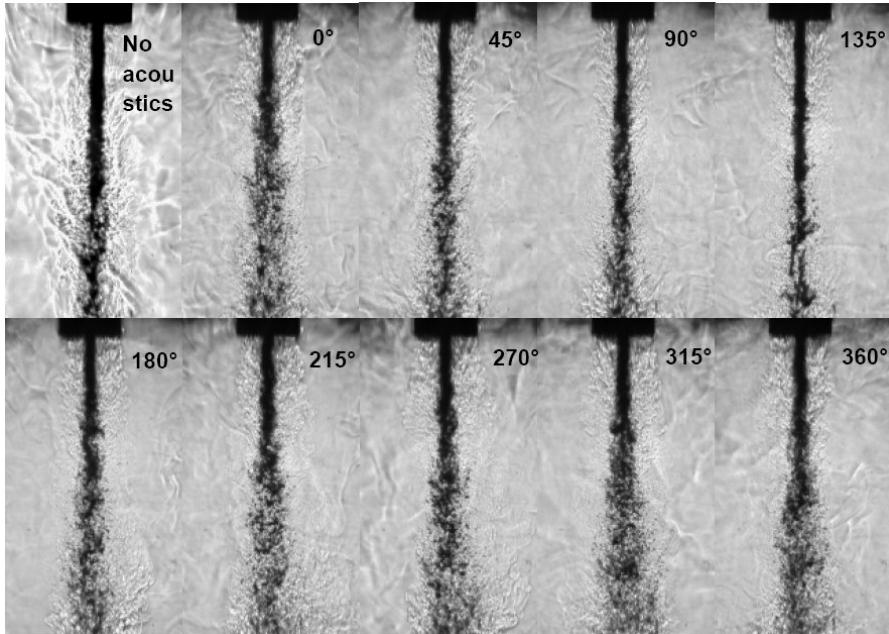
**Sampling Frequency=41kHz, Driving frequency=3.05kHz,
Pch=3.5MPa; Pr=1.03; VR=2.68, MR=2.27,**



Subcritical Low J

57

$$P_{\text{chamber}} = 1.5 \text{ MPa} (\text{Pr} = 0.44)$$



$$J = 0.17$$

$$VR =$$

$$\Delta p_{\text{peak-to-peak}} / p_{\text{chamber}} =$$

$$\dot{m}_{\text{outer}} / \dot{m}_{\text{inner}} =$$

thick inner post injector

J = 0.089 with thin inner post injector

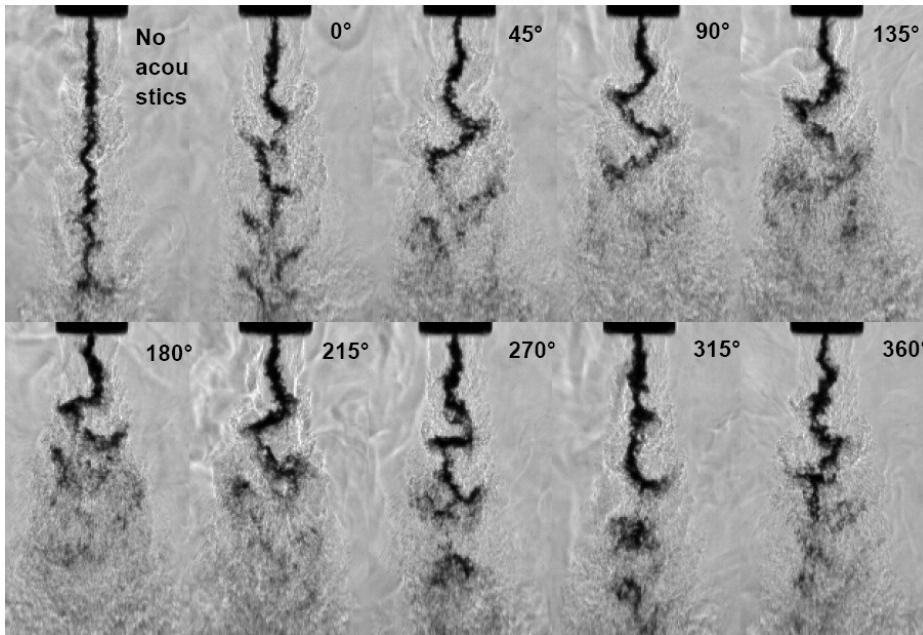
Negligible effect vs. violent destruction of the jet



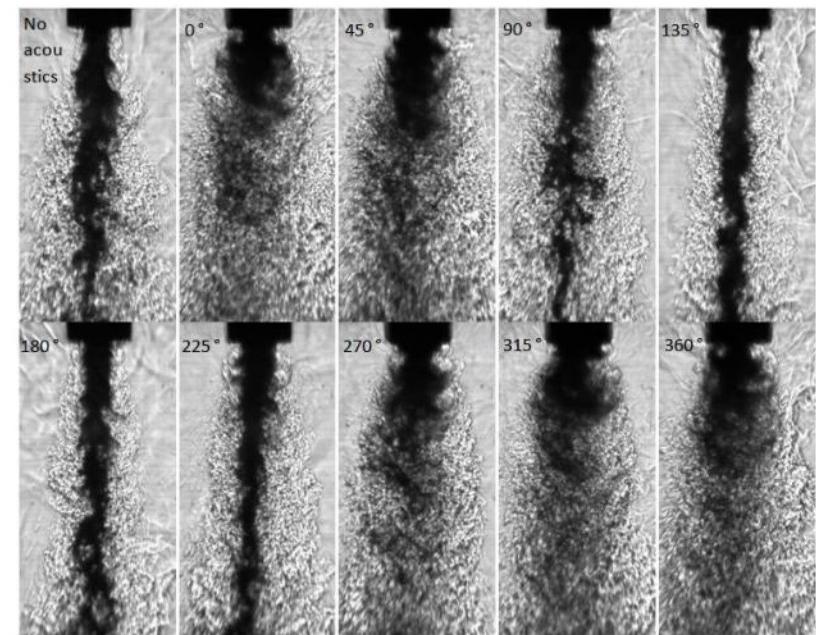
Subcritical Moderate J

58

$$P_{\text{chamber}} = 1.5 \text{ MPa} (\text{Pr} = 0.44)$$



J = 2.6 with thick inner post injector



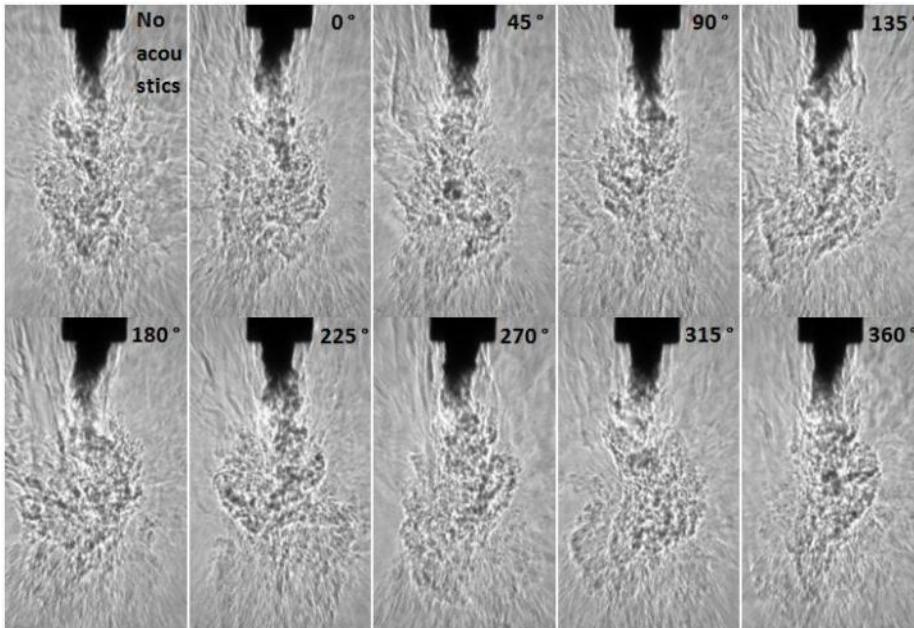
J = 2.0 with thin inner post injector

Bending vs. vortical structures with fine atomization

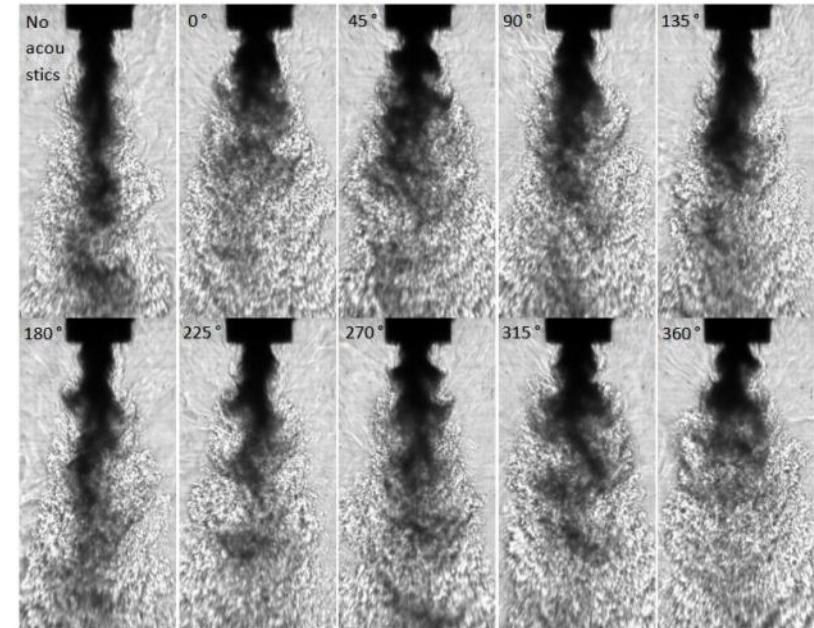
Subcritical Large J

59

$$P_{\text{chamber}} = 1.5 \text{ MPa} (\text{Pr} = 0.44)$$



J = 23 with thick inner post injector



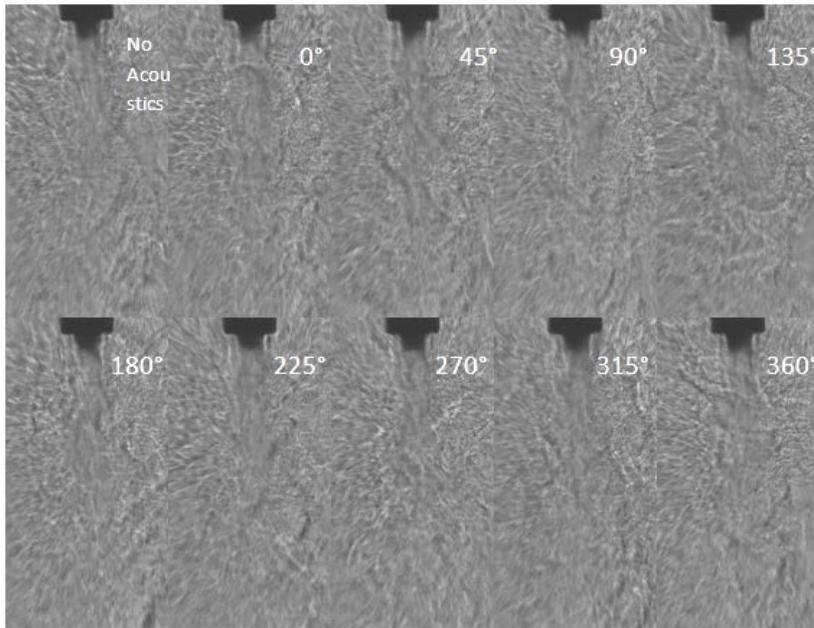
J = 18 with thin inner post injector

Two different mixing mechanisms for similar large J values

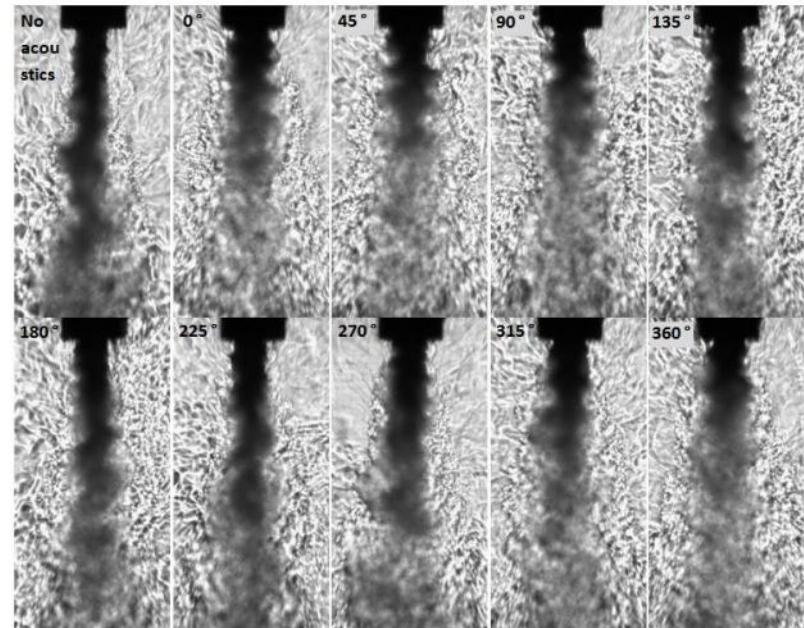
Nearcritical Large J

60

$$P_{\text{chamber}} = 3.6 \text{ MPa} (\text{Pr} = 1.1)$$



$J = 9.3$ with thick inner post injector



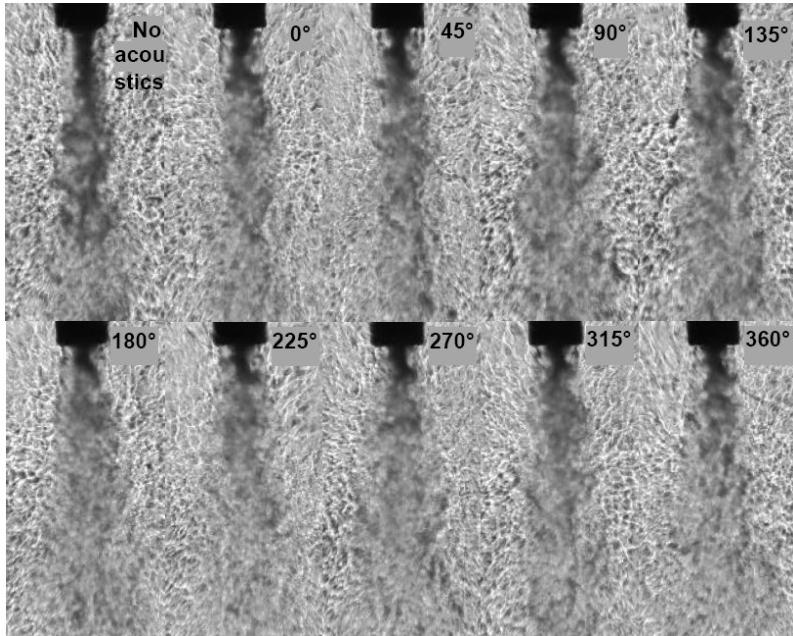
$J = 9.4$ with thin inner post injector

Longer dark core lengths and hence visible effect of acoustics
for thin inner post geometry

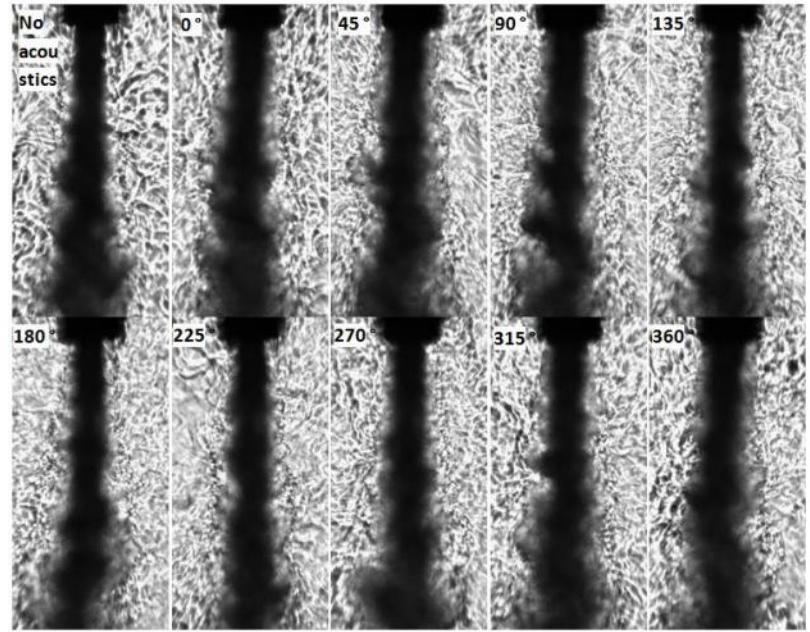
Supercritical Moderate J

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$$P_{\text{chamber}} = 5.0 \text{ MPa} (\text{Pr} = 1.5)$$



$J = 2.4$ with thick inner post injector



$J = 2.6$ with thin inner post injector

Large dark core lengths for the thin post geometry prevent us from observing acoustic effects, if any

thick inner post injector

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	T _{chamber} (K)	P _{chamber} (kg/m ³)	P _{chamber} (MPa)	T _{outer} (K)	\dot{m} _{outer} (mg/s)	P _{outer} (kg/m ³)	u _{outer} (m/s)	Re _{outer} (10 ⁴)	T _{inner} (K)	\dot{m} _{inner} (mg/s)	P _{inner} (kg/m ³)	u _{inner} (m/s)	Re _{inner} (10 ⁴)	L/D ₁ (baseline)	Freq. (kHz)	P' _{RMS max} (kPa)	VR	J
SUB																		
sub1	233	22.0	1.50	191	310	27.6	4.30	0.768	109	279	630	2.2	1.2	26.2	2.98	21.5	2.0	0.17
sub2	231	22.2	1.50	183	790	28.8	11.0	2.02	109	283	630	2.2	1.2	17.1	3.06	20.1	4.8	1.0
sub3	226	21.9	1.45	183	1230	27.8	16.9	3.16	109	284	630	2.2	1.2	16.6	3.06	17.8	7.6	2.6
sub4	226	22.9	1.51	185	1560	28.7	20.9	3.96	109	279	630	2.2	1.2	15.2	2.96	15.7	9.5	4.2
sub5	210	24.9	1.50	182	2400	29.3	31.3	6.18	109	279	630	2.2	1.2	8.40	3.01	16.9	14	9.6
sub6	216	24.1	1.50	191	3640	27.7	50.3	9.02	109	279	630	2.2	1.2	5.63	3.02	16.3	23	23
NEAR																		
near1	223	56.6	3.58	180	1060	75.4	5.38	2.58	123	290	520	2.8	2.0	24.4	3.08	9.04	2.0	0.55
near2	207	62.0	3.57	152	1570	101	5.95	4.16	117	289	590	2.4	1.5	15.5	3.04	10.8	2.5	1.0
near3	228	55.1	3.58	185	1590	72.4	8.40	3.80	126	293	440	3.3	2.5	14.6	3.00	11.8	2.6	1.1
near4	223	56.1	3.55	184	2170	72.3	11.5	5.21	127	294	360	4.0	3.4	12.1	3.01	11.4	2.8	1.6
near5	230	54.2	3.56	199	2120	65.1	12.5	4.84	126	292	440	3.3	2.5	12.9	3.03	12.1	3.8	2.1
near6	229	54.5	3.56	183	2690	73.1	14.1	6.48	126	292	420	3.4	2.5	5.98	3.05	11.1	4.1	2.9
near7	219	57.6	3.56	194	3080	67.4	17.5	7.15	125	289	480	3.0	2.2	5.56	3.06	11.8	5.9	4.9
near8	213	59.6	3.56	192	6460	68.3	36.2	15.1	128	295	220	6.6	5.2	2.45	2.93	9.73	5.5	9.3
SUPER																		
super1	231	76.1	4.96	198	292	93.9	1.19	0.642	136	291	300	4.8	3.9	37.7	3.05	8.01	0.25	0.019
super2	231	76.1	4.96	193	997	97.7	3.90	2.22	130	292	460	3.1	2.4	26.7	3.01	10.2	1.2	0.33
super3	221	80.4	4.95	180	2050	109	7.19	4.72	128	291	490	2.9	2.1	19.2	3.01	10.7	2.5	1.3
super4	222	80.1	4.96	182	3110	107	11.1	7.13	134	288	360	3.9	3.3	10.2	3.05	10.1	2.8	2.4
super5	222	80.3	4.97	191	2820	99.5	10.8	6.32	131	293	440	3.3	2.6	9.02	3.09	12.5	3.3	2.5
super6	211	85.8	4.96	187	5820	103	21.6	13.2	132	286	410	3.4	2.7	3.04	3.05	10.7	6.3	9.9

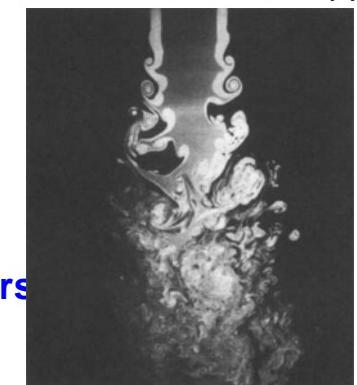
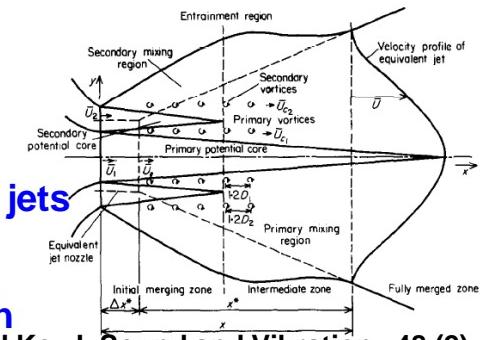


New Injector

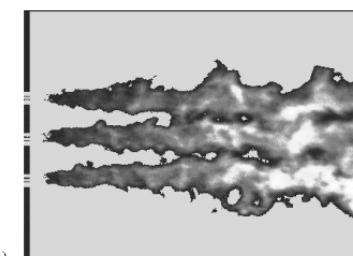
	T _{chamber} (K)	P _{chamber} (kg/m ³)	P _{chamber} (MPa)	T _{outer} (K)	\dot{m} _{outer} (mg/s)	P _{outer} (kg/m ³)	u _{outer} (m/s)	Re _{outer} (10 ⁴)	T _{inner} (K)	\dot{m} _{inner} (mg/s)	P _{inner} (kg/m ³)	u _{inner} (m/s)	Re _{inner} (10 ⁴)	L/D ₁ (baseline)	Freq. (kHz)	P ['] _{RMS max} (kPa)	VR	J
SUB																		
subnew1	235	22	1.48	199	90	26	1.4	0.21	105	920	660	0.91	1.3	13+	3.01	8.86	1.5	0.089
subnew2	237	22	1.49	197	200	26	3.0	0.47	106	925	655	0.92	1.3	13+	2.96	14.0	3.3	0.43
subnew3	246	21	1.49	195	450	27	6.6	1.1	109	925	630	0.96	1.5	11+	2.97	12.1	6.9	2.0
subnew4	224	23	1.49	189	600	28	8.5	1.5	110	925	620	0.97	1.5	10.4	3.04	10.2	8.7	3.4
subnew5	217	24	1.49	184	750	29	10	1.9	110	925	620	0.97	1.5	9.29	3.02	11.5	11	5.2
subnew6	228	22	1.49	193	880	27	13	2.1	108	925	640	0.94	1.4	8.08	2.96	12.7	14	7.8
subnew7	222	23	1.49	194	1100	27	16	2.6	108	925	640	0.94	1.4	7.63	2.92	11.2	17	12
subnew8	217	24	1.48	201	1300	26	20	3.0	109	925	630	0.96	1.5	7.26	2.90	9.16	21	18
NEAR																		
nearnew1	228	55	3.56	213	330	60	2.2	0.70	109	925	650	0.93	1.3	14+	2.98	10.8	2.3	0.50
nearnew2	226	55	3.56	209	460	61	3.0	1.0	109	925	650	0.93	1.3	14+	3.06	9.17	3.2	0.97
nearnew3	230	54	3.58	198	730	66	4.3	1.6	108	925	655	0.92	1.3	13+	3.00	9.12	4.7	2.2
nearnew4	216	59	3.58	199	1030	65	6.3	2.3	109	925	650	0.93	1.3	13+	3.11	16.0	6.7	4.6
nearnew5	214	59	3.58	203	1460	63	9.2	3.2	109	925	650	0.93	1.3	7.01	3.07	15.0	9.9	9.4
nearnew6	215	59	3.56	207	2060	62	13	4.5	111	925	635	0.95	1.4	3.55	3.09	18.3	14	19
SUPER																		
supernew1	219	81	4.95	212	890	85	4.1	1.8	111	925	650	0.93	1.4	13+	3.11	17.0	4.4	2.6

Highlights from previous work 1/2

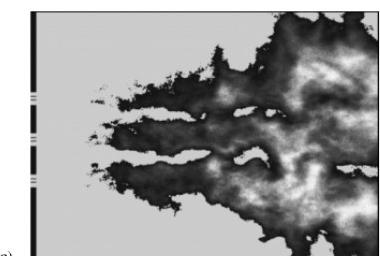
- Crow and Champagne, 1971
 - Single jet preferred mode, $St=fd/U \sim 0.3$
- Ko et al, 1976-1989
 - Some of earliest detailed description of near field mixing for coaxial jets
- Boldman et al, 1975
 - Experimental and theoretical analysis for mixing of two streams with different velocities – points out different vortex interactions Kwan and Ko, J. Sound and Vibration, 48 (2), 1976
- Gutmark and Ho, 1983
 - Collects previous results on jet preferred mode, St has a range from ~0.24-0.64
- Dahm et al, 1992
 - Points out importance of layer thickness and velocity defect on shear layers seminal pictures of different instabilities
- Villermeaux 1998
 - Inner jet core length expression, $L/D_1 = 6/J^{0.5}$
- Richecoeur et al (Candel's group), 2006
 - Forced transverse acoustic excitation of flames



Dahm et al, JFM (241) 1992



Richecoeur et al, JPP (22) No 4, 2006

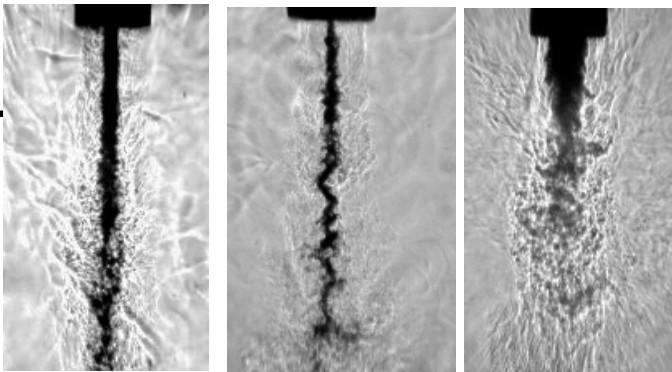




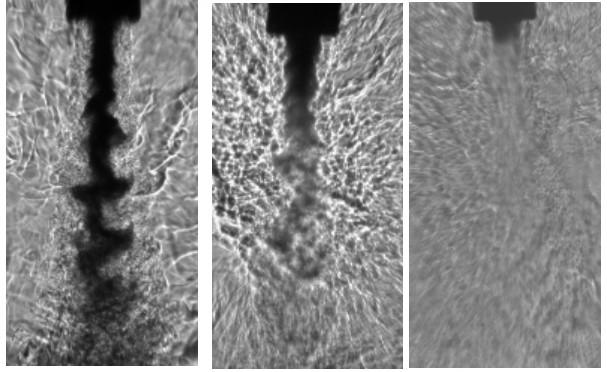
Short Thick post behavior families

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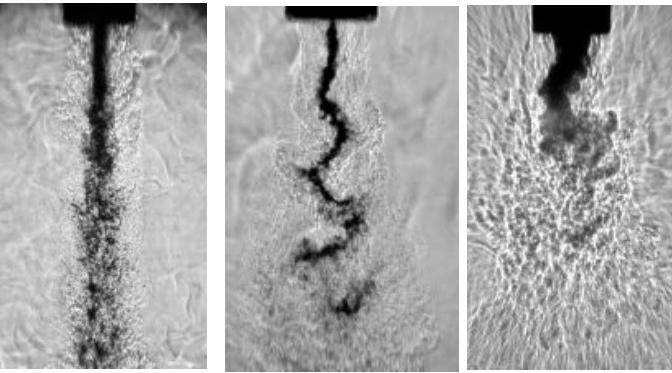
Base-line



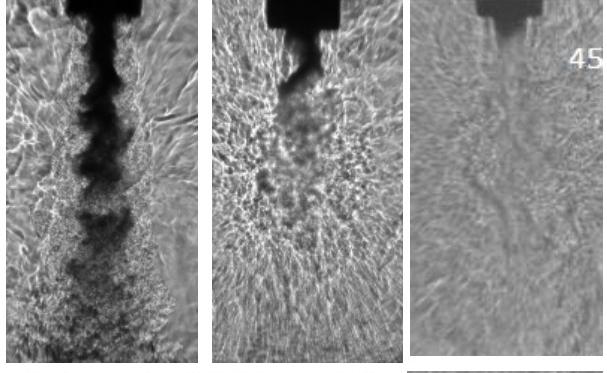
- Subcritical conditions**
- Acoustics undulate inner jet like in Heidmann's experiments consistent with being driven by an imposed velocity field
 - Reductions of core of more than 20% for $0.2 < J < 10$



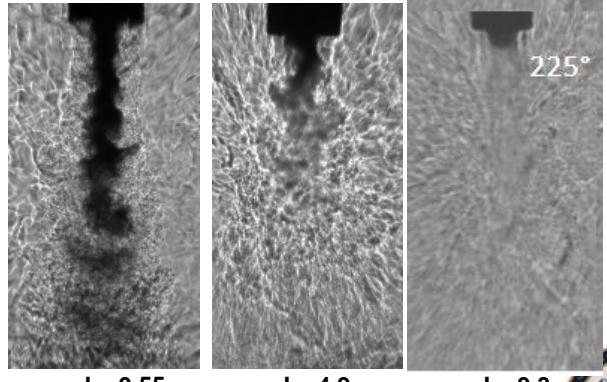
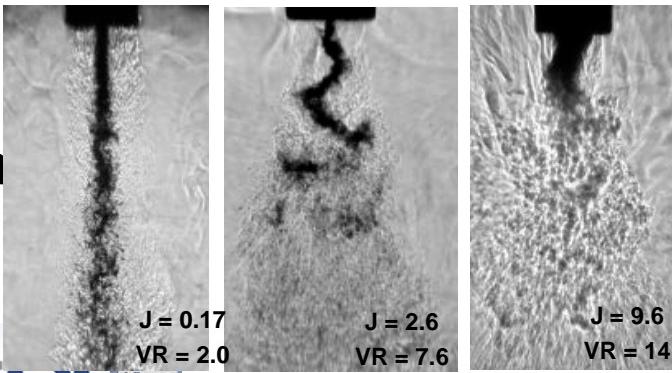
Max Δp



- Near and supercritical conditions**
- Less undulation on inner jet but same mode
 - Not a clear effect of phase on the reduction of the dark core length
 - Max reduction of inner jet occurred at $1 < J < 5$



Min Δp



Conditions of Interest

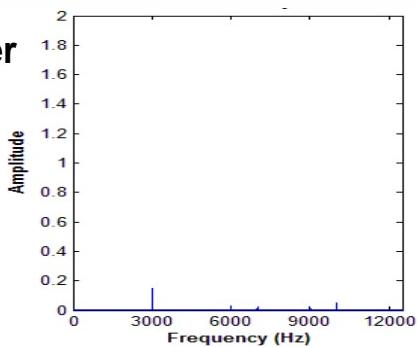
Run Date	T _{chamber} (K)	ρ _{chamber} (kg/m ³)	P _{chamber} (MPa)	T _{outer} (K)	M _{outer} (mg/s)	ρ _{outer} kg/m ³	u _{outer} (m/s)	Re _{outer} (10 ⁴)	T _{inner} (K)	M _{inner} (mg/s)	ρ _{inner} kg/m ³	u _{inner} (m/s)	Re _{inner} (10 ⁴)	Freq. (kHz)	VR	J	Recess
2010_02_18	233	52	3.49	165	1330	84	6.25	3.3	118	938	576	1.06	1.8	3.00	5.9	5.1	D1
2010_03_26	201	63	3.52	184	5976	72	32.97	17	129	2408	185	8.50	14	3.05	3.9	5.9	D1
2010_06_21 case1	234	53	3.54	191	814	68	4.74	1.9	130	333	175	1.26	2.4	3.08	3.8	5.5	0.5D1
2010_06_30 case1	174	78	3.51	161	4732	88	21.3	12	117	3199	586	3.56	6.0	3.02	6.0	5.4	0.5D1



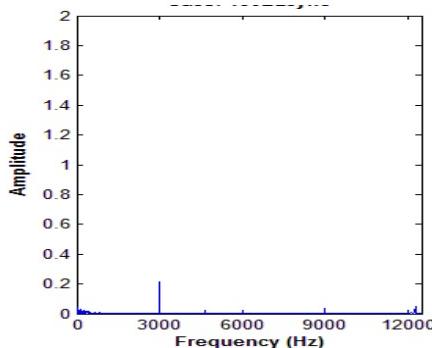
Synchronized p' and images: Pr=1.03, J=5.1, VR=5.9

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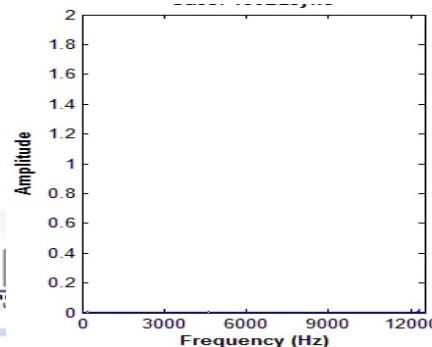
Center



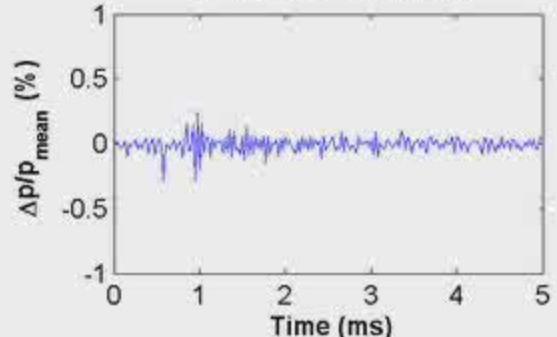
Outer



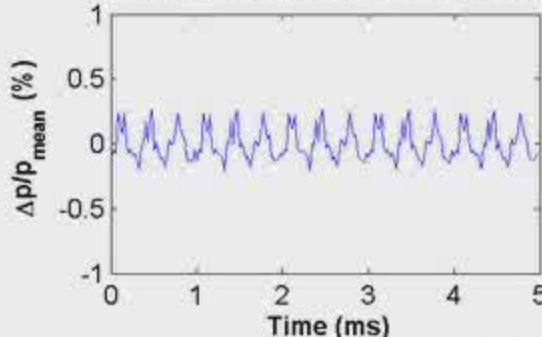
Inner



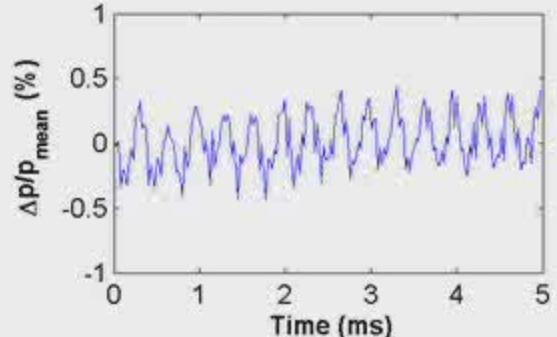
Inner Jet Pressure



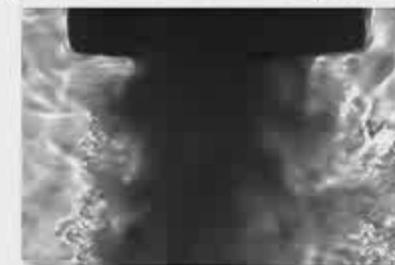
Chamber Wall Center Pressure



Outer Jet Pressure



Inner Injector Recessed 0.5 D_i
Pr = 1.03, J = 5.1, VR = 5.9
Forcing Condition: 3000 Hz, Minimum Δp



Feb 18, 2010

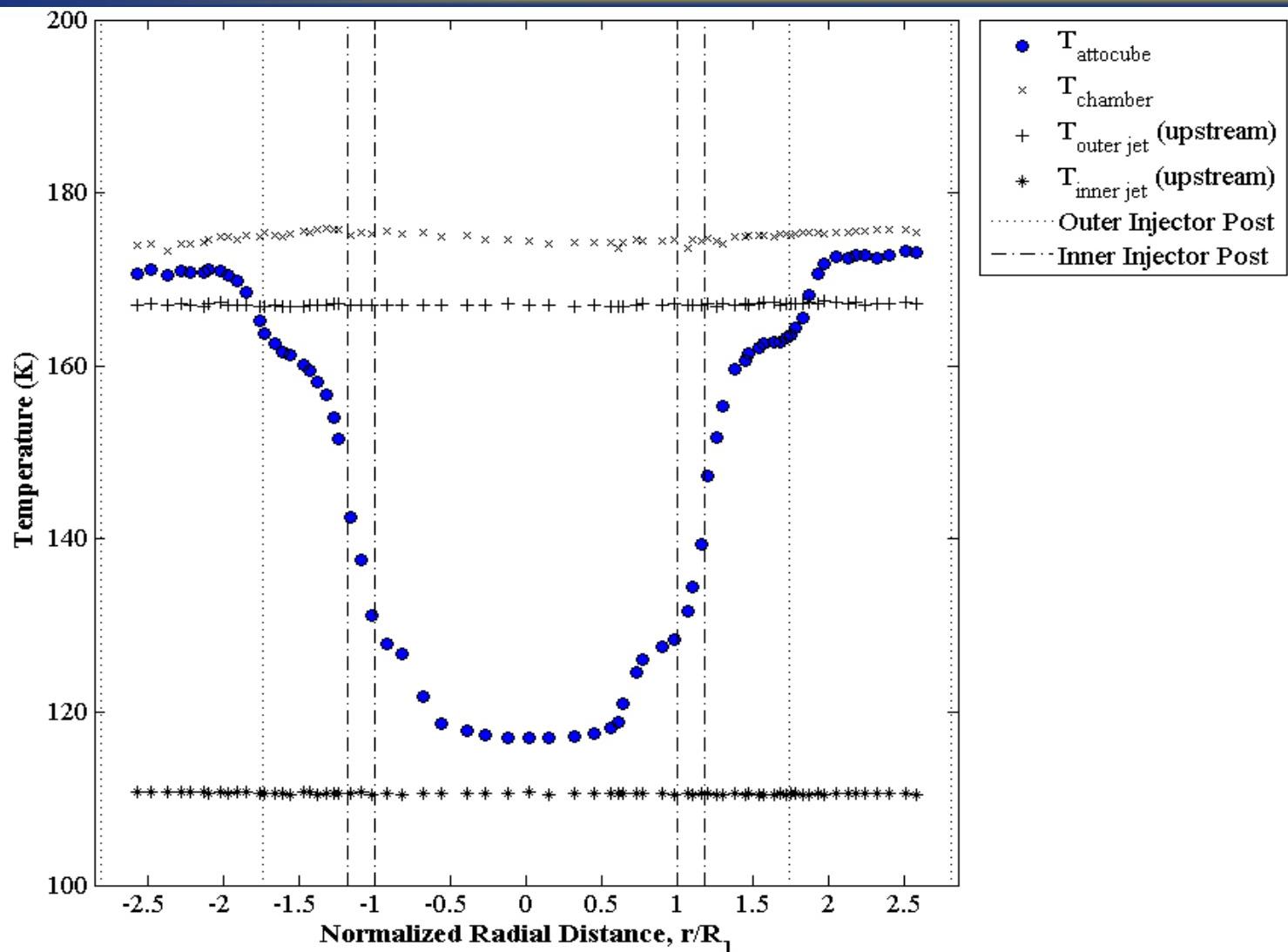
Uo=6.25 m/s, Ui=1.06 m/s, To=165K , Ti=118 K

MOVIE



Jet Temperature Profiles

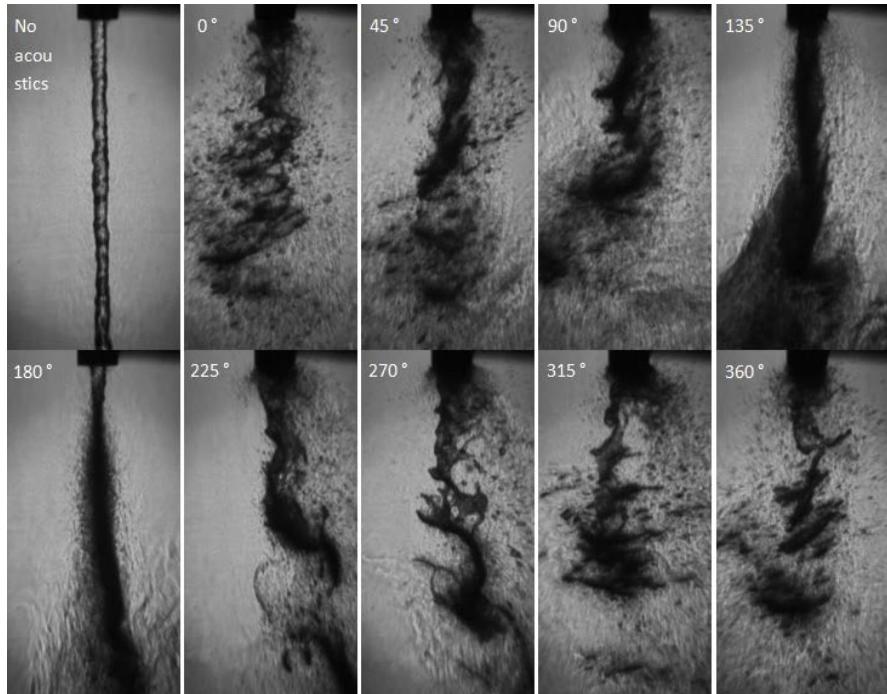
68



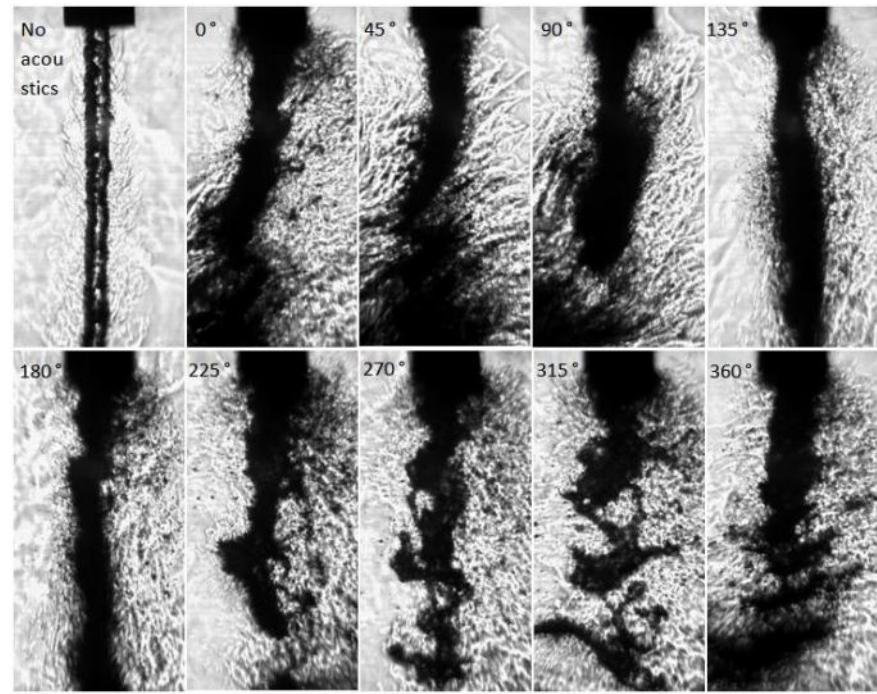


Effect of Recess: SAR_ThinLip; Pr=0.45, J~0.09

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Flush inner post, $J=0.09$, $p'/p=0.45\%$

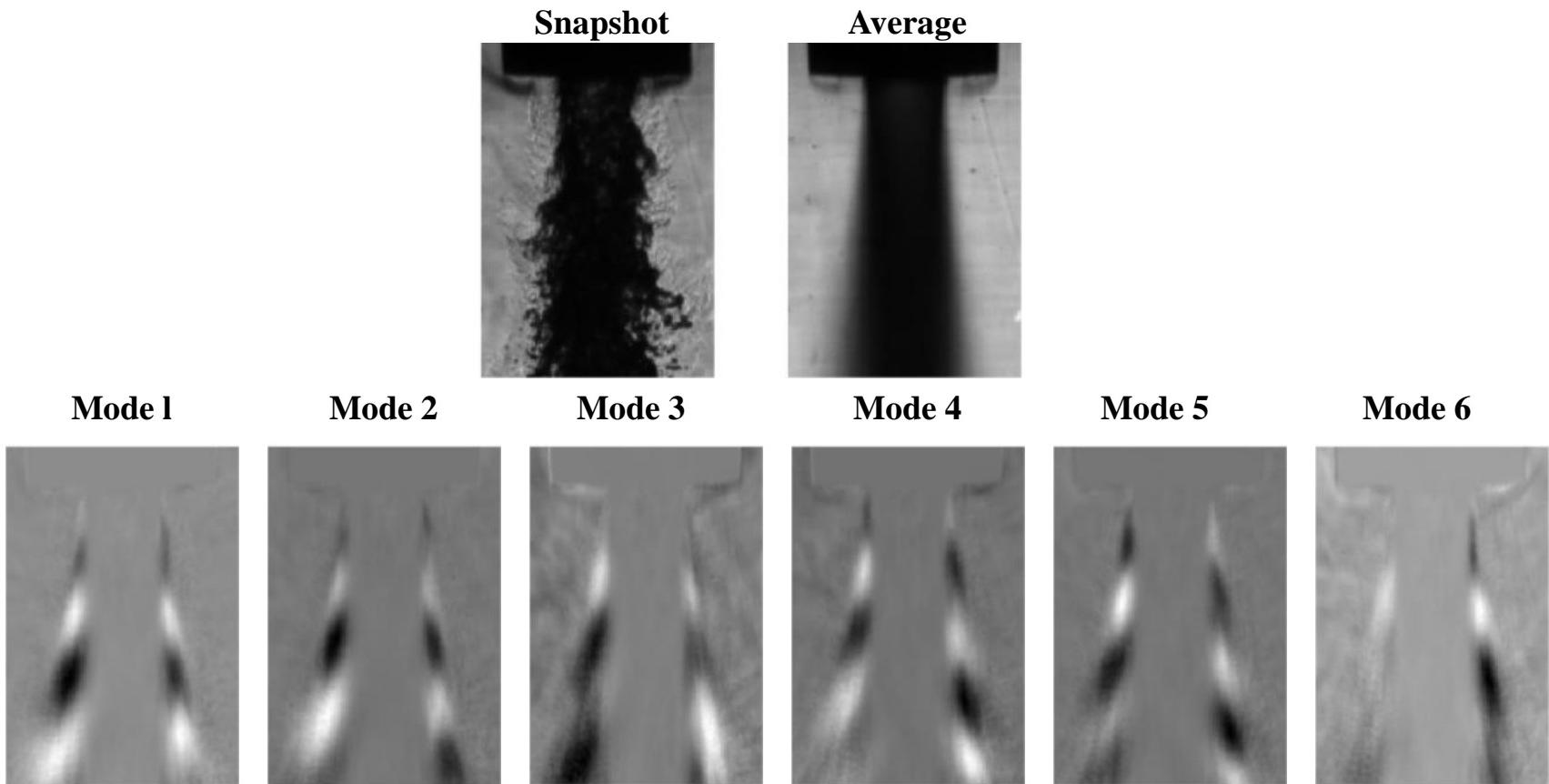


Recessed inner post, $J=0.089$, $p'/p=0.60\%$

Qualitatively similar at very low J values

Case I: Baseline Flow

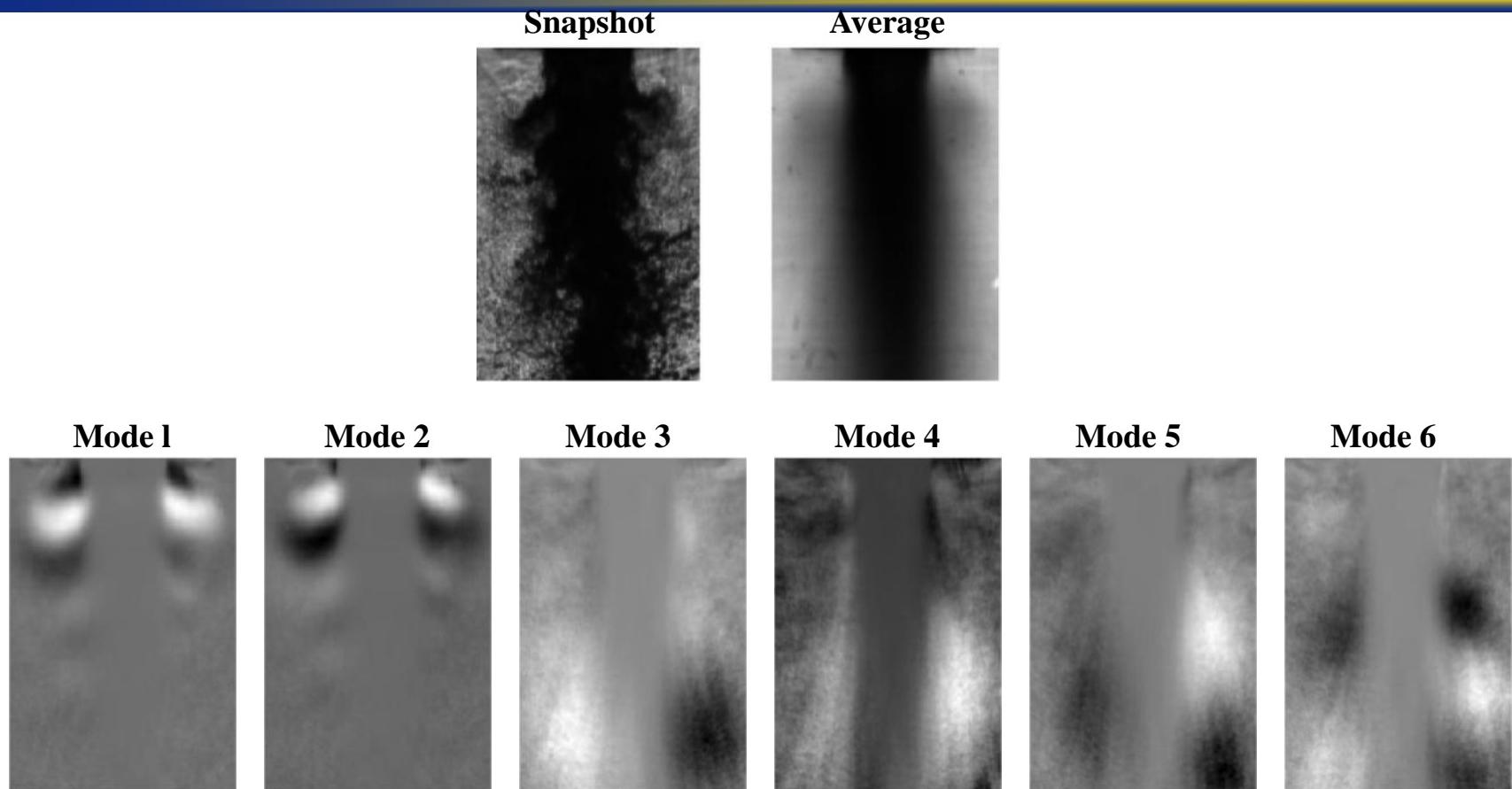
70



Case	P_R	$T_{R,OJ}$	$T_{R,IJ}$	R	J
I	0.44	1.19	0.84	5.8	2.0

Case I: Acoustically Forced Flow

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Case	P_R	$T_{R,OJ}$	$T_{R,IJ}$	R	J	f (kHz)
I	0.44	1.19	0.84	5.8	2.0	2.96